THE EFFECTIVENESS OF ROBOT-ASSISTED, TASK-SPECIFIC ANKLE TRAINING IN IMPROVING DEFICITS ACROSS THE THREE DOMAINS OF THE ICF IN CHILDREN WITH CEREBRAL PALSY (CP)

Madawi H. Alotaibi

Submitted to the faculty of the University Graduate School

in partial fulfillment of the requirements

for the degree

Doctor of Philosophy

in the School of Health and Human Sciences,

Indiana University

November 2018

Accepted by the Graduate Faculty of Indiana University, in partial fulfillment of the requirements for the degree of Doctor of Philosophy.

Doctoral Committee

Brent Arnold, PhD, ATC, Co-Chair

Peter Altenburger, PhD, PT, Co-Chair

May 4, 2018

Niki Munk, PhD, LMT

Tracy Dierks, PhD

DEDICATION

This dissertation is dedicated to my parents, husband, brothers, sisters, and children, all of whom made multiple sacrifices over the years to help me pursue my dream. Without their support and encouragement, I would not have had the time or the effort needed to complete this degree. I love you all.

ACKNOWLEDGEMENT

I would like to extend my deep appreciation to my advisor, Peter Altenburger, Ph.D, PT, for his guidance, support, and the wealth of knowledge he provided me for the past several years. I would also like to thank my committee members Brent Arnold Ph.D, Tracy Dierks Ph.D, and Niki Munk Ph.D for the knowledge each brought to this research. A special thank you for everyone who helped with data collection and analysis: Amy Bayliss DPT, PT, Emily Fuller, Katherine Bridgeman, George Eckert, and many DPT students. I would also like to express my gratitude to the robotics lab staff at the IU Neuroscience Center for their valuable help, especially Ryan Cardinal DPT, PT, and Jeff Frame. I would like to extend my appreciation to all children and their families who participated in my research.

I also want to express my deepest gratitude to my loving and generous parents. Without their support, I would not have had the opportunities that have gotten me to this point. Thank you so much, Mom and Dad. I also would like to thank my brothers and sisters—Ohoud, Faisal, Kholoud, Mohammed, Rashed, Saad, and Nawaf—for supporting, loving, and encouraging me throughout this journey. Finally, I would like to thank my husband, Fahad who stood by me through the good and bad times, and my children—Mohammed, Abdullah, and Milla—who were always there to cheer me up.

Madawi H. Alotaibi

THE EFFECTIVENESS OF ROBOT-ASSISTED, TASK-SPECIFIC ANKLE TRAINING IN IMPROVING DEFICITS ACROSS THE THREE DOMAINS OF THE ICF IN CHILDREN WITH CEREBRAL PALSY (CP)

Background: Cerebral Palsy (CP) is considered to be the leading cause of motor disability among children. Children with CP present with multiple physical impairments including decreased strength and range of motion (ROM), increased spasticity, and poor balance and coordination. These impairments often lead to limitations in ankle motor control that impacts balance and gait function, which puts children at a higher risk for developing other problems. In recent studies, robotic devices have been developed to address poor motor control of the upper and lower extremities.

Aim: The aim of this study is to investigate the extent to which the robot-assisted, task-specific ankle trainer improve deficits across the three domains of the International Classification of Functioning, Disability and Health (ICF) in children with CP.

Method: This is a quasi-experimental, single group, repeated measure design with four time-testing points through a set training session/protocol. A convenience sample of 5 children with CP were enrolled in the study. All children received 6-weeks of ankle robot training that included two 45-60 minute sessions per week, for a total of 12 sessions. Data from Tardieu Scale of spasticity, Boyd and Graham selective motor control, Pediatric Balance Scale, goniometer, hand held dynamometer, gait mat analysis, accelerometer, LIFE-H for children questionnaires, ultrasound, and robotic evaluation were collected at the different time points (1 week and 1 month pre training and 1 week and 1 month post training). Descriptive statistics and repeated measure (ANOVA) were used with SPSS software for data analysis.

Results: All participants showed improvement in 1. Body Function and Structures (ROM, tone, strength, balance, ankle control and performance, and muscle architecture), 2. Activity (gait and activity counts) and 3. Participations over the course of the study.

Conclusion: The results revealed the potential of robot-assisted, task-specific ankle training to improve motor performance and capacity at the body function, activity and participation level. Training appeared to have a lasting impact as most gains were maintained one month following training.

Brent Arnold, PhD, ATC, Co-Chair

Peter Altenburger, PhD, PT, Co-Chair

TABLE OF CONTENTS

LIST OF TABLES xii

LIST OF FIGURES xvi

LIST OF ABBREVIATIONS xix

DEFINITIONS xxii

CHAPTER I. INTRODUCTION 1

Background of the Problem 1

Motor Abnormalities 1

Associated Impairments 3

Anatomic and Radiological Findings 3

Causation and Timing 4

Statement of Problem 4

Purpose of the Study 5

Research Questions/Aims/Hypotheses 5

Significance 8

Theoretical Framework 11

Neuroplasticity 12

Motor Learning 17

Dynamic System Theory (DST) 18

CHAPTER II. LITERATURE REVIEW 20

Cerebral Palsy 20

Current Approaches 22

Drawbacks of Current Approaches 24

Development of Robotics-Based Approaches 24
Advantages of Assisted Robotics Therapy 25
High-repetition 25
Task Specificity 26
Measurement Tool 26
Engaging and Motivating 26
Increase Patients' Compliance 27
Active Assisted (As Needed) 27
Work Efficiency 27
Cost- and Time-efficient 27
Previous Work in Upper-Limb Robotics 28
Adult Studies 28
Children Studies 29
Previous Work in Lower-Limb Robotics 31
Children Studies 32
Introducing Ankle Robotics and Its Challenges 33
The Uniqueness of Ankle Robotics 34
The Importance of the Ankle/Foot 34
The Severity of Ankle Involvement 35
Ankle Joint in Relation To Other Joints 36
Studies on Ankle Robotics 37
Gap in Literature 37
CHAPTER III. METHODS 39

Study Design 39
Participants 39
Outcome Measurements 40
Body Function and Structures 42
Activity 55
Participation 57
Description of The Ankle Robot “Anklebot” 58
Intervention 59
Data Collection 61
Data Management 61
Data Analysis 62
CHAPTER IV. RESULTS 64
Characteristics of the Study Sample 64
Data Findings 66
1. Body Function and Structures Level 66
2. Activity Level 119
3. Participation Level 131
Adverse Events 136
CHAPTER V. DISCUSSION 137
Aims and Findings 137
1. Body Function and Structures Level Changes 139
2. Activity Level Changes 156
3. Participation Level Changes 164

Limitations ... 168
Implication for Practice ... 169
Implication for Future Research ... 170
CHAPTER VI. CONCLUSION ... 172
APPENDICES ... 174
Appendix 1: IRB Approval ... 174
Appendix 2: Consent Form ... 178
Appendix 3: Assent Form ... 182
Appendix 4: Study’s Flyer ... 185
Appendix 5: List of Clinics ... 186
Appendix 6: Evaluation Form ... 188
Appendix 7: Robotic Evaluation ... 198
Appendix 8: LIFE-H for Children Form ... 201
Appendix 9: Prescreening Form ... 209
REFERENCES ... 216
CURRICULUM VITAE

LIST OF TABLES

Table 1. Study's outcomes of interest, how they are measured and when measurement occurred. 41

Table 2. Goniometer's administration to assess ROM 44

Table 3. Dynamometer positioning and administration.. 47

Table 4. Anklebot Protocol: the 3 games that children played and the repetitive movements associated with each game.. 60

Table 5. Description of the study aims and the statistical tests 62

Table 6. Participants' characteristics 66

Table 7. Mean ± SD ankle dorsiflexion strength (N) changes prior to and after training. 67

Table 8. Post hoc test showed the difference between time points.................................. 67

Table 9. Mean ± SD ankle eversion strength (N) changes prior to and after training 68

Table 10. Post hoc test showed the difference between time points................................ 68

Table 11. Mean ± SD ankle inversion strength (N) changes prior to and after training 69

Table 12. Post hoc test showed the difference between time points................................ 69

Table 13. Mean ± SD ankle plantarflexion strength (N) changes prior to and after training 70

Table 14. Post hoc test showed the difference between time points................................ 71

Table 15. Mean ± SD knee strength (N) changes prior to and after training.................... 73

Table 16. Post hoc test showed the difference between time points................................ 74

Table 17. Mean ± SD hip abduction strength (N) changes prior to and after training 76

Table 18. Post hoc test showed the difference between time points 76

Table 19. Mean ± SD hip adduction strength (N) changes prior to and after training 77

Table 20. Post hoc test showed the difference between time points 77

Table 21. Mean ± SD hip extension strength (N) prior changes to and after training...... 78

Table 22. Post hoc test showed the difference between time points 78

Table 23. Mean ± SD hip flexion strength (N) changes prior to and after training.......... 79

Table 24. Post hoc test showed the difference between time points 79

Table 25. Mean ± SD Tardieu Scale of Spasticity (deg.) changes prior to and after training 82

Table 26. Post hoc test showed the difference between time points 82

Table 27. Mean ± SD CSA of AT, TA and gastrocnemius changes prior to and after training 85

Table 28. Mean ± SD TA pennate angle (deg.) changes prior to and after training......... 86

Table 29. Mean ± SD TA thickness (mm) changes prior to and after training................. 86

Table 30. Mean ± SD ankle dorsiflexion (DF) ROM (deg.) changes prior to and after training 89

Table 31. Post hoc test showed the difference between time points 89

Table 32. Mean ± SD ankle plantarflexion (PF) ROM (deg.) changes prior to and after training 91

Table 33. Post hoc test showed the difference between time points 91

Table 34. Mean ± SD ankle eversion ROM (deg.) changes prior to and after training 93

Table 35. Post hoc test showed the difference between time points 93

Table 36. Mean ± SD ankle inversion ROM (deg.) changes prior to and after training 95
Table 37. Post hoc test showed the difference between time points 95
Table 38. Mean ± SD knee extension ROM (deg.) changes prior to and after training 98
Table 39. Post hoc test showed the difference between time points 98
Table 40. Mean ± SD knee flexion ROM (deg.) changes prior to and after training 102
Table 41. Post hoc test showed the difference between time points 102
Table 42. Mean ± SD hip abduction (AB) ROM (deg.) changes prior to and after training 105
Table 43. Post hoc test showed the difference between time points 105
Table 44. Mean ± SD hip adduction (ADD) ROM (deg.) changes prior to and after training 107
Table 45. Post hoc test showed the difference between time points 107
Table 46. Mean ± SD hip extension (EX) ROM (deg.) changes prior to and after training 109
Table 47. Post hoc test showed the difference between time points 109
Table 48. Mean ± SD hip flexion (FX) ROM (deg.) changes prior to and after training 111
Table 49. Post hoc test showed the difference between time points 111
Table 50. Mean ± SD Boyd and Graham Selective Motor Control test changes prior to and after training 113
Table 51. Post hoc test showed the difference between time points 113

Table 52. Mean ± SD ankle accuracy (mm) and smoothness (%) changes prior to and after training 115

Table 53. Change in PBS balance scores prior to and after training 117

Table 54. Post hoc test showed the difference between time points 118

Table 55. Mean ± SD gait parameters changes prior to and after training 121

Table 56. Post hoc test showed the difference between time points 122

Table 57. Mean ± SD single support % changes prior to and after training 125

Table 58. Post hoc test showed the difference between time points 126

Table 59. Mean ± SD EE changes prior to and after training 128

Table 60. Post hoc test showed the difference between time points 128

Table 61. Mean ± SD number of steps and TAC changes prior to and after training 130

Table 62. Post hoc test showed the difference between time points 130

Table 63. Mean ± SD LIFE-H categories changes prior to and after training 135

Table 64. Significant study's findings organized by ICF domain and affected side 138

LIST OF FIGURES

Figure 1. The Gross Motor Function Classification System (GMFCS) assessment tool (Palisano et al., 2007). 2

Figure 2. ICF model (WHO, 2015).......... 6

Figure 3. InMotion Technologies Anklebot, Watertown, MA 34

Figure 4. Study Design 39

Figure 5. Study Overview 40

Figure 6. Boyd and Graham Selective Motor Control Test (Groenestijn & van Schie).......... 44

Figure 7. MicroFet 2 HHD (Hoggan Health, Salt Lake City, UT) 46

Figure 8. An example of how to estimate PA 53

Figure 9. Positioning for scanning the Achilles tendon (Backhaus et al., 2001) 53

Figure 10. Positioning for scanning the tibialis anterior (Backhaus et al., 2001) 54

Figure 11. Positioning for scanning the medial gastrocnemius (Chen et al., 2009) 54

Figure 12. Graphic visualization of the Child's performance.......... 55

Figure 13. The Zeno Walkway by ProtoKinetics 56

Figure 14. Actical accelerometer (Philips respironics, Bend, Oregon) 56

Figure 15. The anklebot video games (Michmizos & Krebs, 2012).......... 61

Figure 16. Flow diagram for subject in this study 65

Figure 17. Ankle strength improvement chart 71

Figure 18. Change of ankle muscle strength prior to and after training 71

Figure 19. Knee strength improvement chart 74

Figure 20. Change of knee muscle strength prior to and after training 75

Figure 21. Hip strength improvement chart 79
Figure 22. Change of hip muscle strength prior to and after training 80
Figure 23. Muscle tone improvement chart 83
Figure 24. Change of Tardieu Scale of Spasticity score prior to and after training 83
Figure 25. Ankle muscle architecture change chart 87
Figure 26. Change of ankle muscle architecture mean score prior to and after training 87
Figure 27. Ankle ROM improvement chart 96
Figure 28. Change of (LA) ankle ROM mean score prior to and after training 96
Figure 29. Change of (MA) ankle ROM mean score prior to and after training 97
Figure 30. Knee extension ROM changes chart 99
Figure 31. Change of knee extension ROM mean score prior to and after training 100
Figure 32. Knee flexion ROM changes chart 103
Figure 33. Change of knee flexion ROM mean score prior to and after training 103
Figure 34. Hip ROM improvement chart 111
Figure 35. Change of (LA) hip ROM mean score prior to and after training 112
Figure 36. Change of (MA) hip ROM mean score prior to and after training 112
Figure 37. Ankle control improvement chart 114
Figure 38. Change of Boyd and Graham Selective Motor Control mean score prior to and after training 114
Figure 39. Ankle performance improvement chart 116
Figure 40. Change of ankle performance mean score prior to and after training 116
Figure 41. Change of the PBS mean score prior to and after training 118

Figure 42. Gait parameters improvement chart 122

Figure 43. Change of gait mechanics mean score prior to and after training 123

Figure 44. Comparison of gait mechanics between normal children and children with CP... 123

Figure 45. Comparison of stance % between normal children and children with CP 124

Figure 46. Comparison of swing % between normal children and children with CP..... 124

Figure 47. Comparison of Single support % between normal children and children with CP... 126

Figure 48. Percentage changes of EE (between baseline and follow up) 128

Figure 49. Change of energy expenditure mean score prior to and after training 129

Figure 50. Activity improvement chart... 130

Figure 51. Change of number of steps mean score prior to and after training 131

Figure 52. Change of total activity counts mean score prior to and after training 131

Figure 53. Change of LIFE-H mean score prior to and after training 136

Figure 54. Deficits across the three domains of ICF (WHO, 2002) 139

LIST OF ABBREVIATIONS

ABD	Abduction
ADD	Adduction
ADL	Activity of daily living
AFO	Ankle foot orthosis
AHRQ	Agency for Healthcare Research and Quality
ANOVA	Analysis of variance
APTA	American Physical Therapy Association
AT	Achilles tendon
BTX-A	Botulinum toxin type A
CDC	Centers for Disease Control and Prevention
CIMT	Constraint induced movement therapy
CP	Cerebral Palsy
CSA	Cross-sectional area
DF	Dorsiflexion
DGO	Driven gait orthosis
DOF	Degrees of freedom
DST	Dynamic system theory
EE	Energy expenditure
EP	Epilepsy
EX	Extension
FX	Flexion
HHD	Hand-held dynamometer

GMFCS	Gross Motor Function Classification System
GMFM	Gross Motor Function Measure
ICCs	Intraclass correlation coefficients
ICF	International Classification of Functioning, Disability and Health
IS	Inertial sensors
LA	Less-affected
LIFE-H for Children	Assessment of Life Habits for Children
MA	More-affected
MT	Muscle thickness
NDT	Neurodevelopmental therapy
NIH	National Institutes of Health
PA	Pennation angle
PBS	Pediatric balance scale
PEDI	Pediatric Evaluation of Disability Inventory
PF	Plantar flexion
ROM	Range of motion
6MinWT	Six-minute walk test
SM	Smoothness of movements
TA	Tibialis anterior
TAC	Total activity count
10MWT	Ten-meter walk test
TS	Tardieu scale

WeeFIM	Functional Independence Measure
WHO	World health organization

DEFINITIONS

The terms and concepts used in this study are defined based on the current literature.

Activity	The execution of a mobility task or action by an individual
Body functions	Physiological functions of body systems
Body structures	Anatomical parts of the body
Cerebral palsy	A group of permanent disorders of the development of movement and posture, causing activity limitations that are attributed to non-progressive disturbances that occurred in the developing fetal brain or infant brain. The motor disorders of CP are often accompanied by disturbances of sensation, perception, cognition, communication, and behavior.
Drop foot	Weakness in the dorsiflexors, which are responsible for elevating the foot in the early stance and swing phases
Dynamic system theory	Describes the motor development of human beings across the life span
Motor learning theory	Describes how individuals learn or relearn to perform movement
Neuroplasticity	The brain's ability to reorganize and alter its structure, connection, and function in response to stimuli
Participation	Involvement in a life situation

Robotics	The application of electronic, computerized control systems to mechanical devices designed to perform human functions

CHAPTER I. INTRODUCTION

Background of the Problem

Cerebral palsy (CP) is the most common cause of physical disability among children, affecting at least 2 in 1,000 children born in the United States (Himmelmann et al., 2005; Westbom et al., 2007). These numbers continue to grow because of the increased survival rate among pre-term babies (Nelson, 2002; Reddihough & Collins, 2003). While there have been numerous attempts to define CP over the years, the most up-to-date definition describes it as:

> a group of permanent disorders of the development of movement and posture, causing activity limitations that are attributed to non-progressive disturbances that occurred in the developing fetal brain or infant brain. The motor disorders of CP are often accompanied by disturbances of sensation, perception, cognition, communication, and behavior. (Rosenbaum, Paneth, Leviton, Goldstein, & Bax, 2007, p. 9)

Based on the CP definition, the motor outcome is related to the severity of motor disability. Unfortunately there is no standardized system to classify the motor disability and that’s why CP classification has undergone several revision. Currently, the most accepted classification system is based on four major components, including motor abnormalities (the type of the motor disorder and the functional motor abilities), associated impairments, anatomic and radiological findings, and causation and timing (Bax et al., 2005; Rosenbaum et al., 2007).

Motor Abnormalities

1. The type of motor disorder: Children with CP are classified based on the type of motor disorder they have, which could be spastic (high muscle tone), dyskinetic (involuntary movement), or ataxic (loss of muscle coordination) (Bax et al., 2005). Most of the children have spastic CP, with a prevalence of 77.4% (CDC, 2015).

2. The functional motor abilities: Children with CP can be classified according to their functional abilities by using objective functional measurements, including the Gross Motor Function Classification System (GMFCS) (Palisano et al., 1997; Palisano, Rosenbaum, Bartlett, & Livingston, 2008). The GMFCS is a standardized system that classifies the child's gross motor function on a five-level scale based on sitting, standing, and walking skills, as well as his or her use of an assisted device (Figure 1) (Palisano, Rosenbaum, Bartlett, & Livingston., 2007). This classification system (Figure 1) highlights children's ability rather than their impairments (Palisano, Rosenbaum, Bartlett, & Livingston, 2008). The GMFCS has been found to have good reliability and validity (Palisano et al., 1997).

The GMFCS classifies a child's gross motor function at 5 levels.

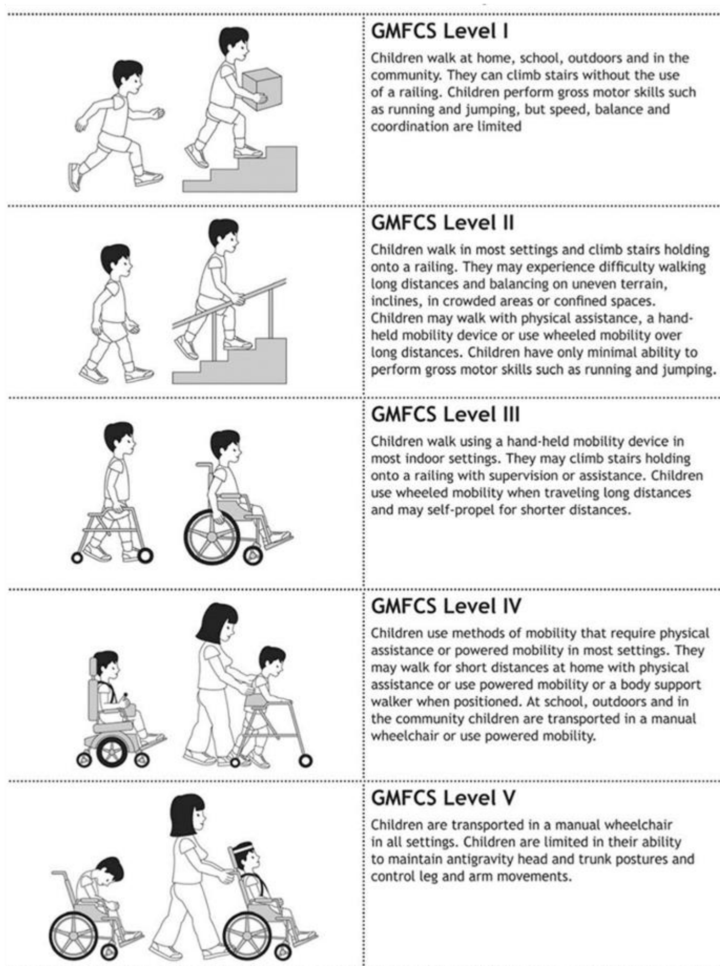


Figure 1. The Gross Motor Function Classification System (GMFCS) assessment tool (Palisano et al., 2007).

Associated Impairments

Children with CP suffer from different impairments associated with their motor disorders that interfere with their ability to carry out everyday tasks. These impairments are classified as present or absent and further described using standardized terminology (Rosenbaum et al., 2007). Studies have shown that more than 50% of children with CP suffer from a variety of associated impairments, including cognitive deficits (40% of children with CP), epilepsy (EP) (33–41% of children with CP), hearing and visual problems (19% of children with CP), and communication impairments (CDC, 2015; Himmelmann, Beckung, Hagberg, & Uvebrant, 2006; Nordmark, Hägglund, & Lagergren, 2001).

Anatomic and Radiological Findings

Another form of classifying children with CP is according to the impairment's anatomical location in the arms, legs, or trunk and whether one or both limbs are involved. The common classifications are hemiplegia, diplegia, triplegia, and quadriplegia (Miller, 2005). Hemiplegia refers to involvement of the upper and lower limb on the same side; diplegia refers to involvement of both lower limbs; triplegia means involvement of both lower limbs and one of the upper limbs; quadriplegia refers to the involvement of both lower and upper limbs in addition to the trunk (Miller, 2005). The radiological findings can help in describing the impairments, but there is no specific classification system that can be used.

Causation and Timing

Identifying the exact time of the insult is often used as a form of classification, which can be either a prenatal or post-natal insult, although this time is not always known.

Statement of Problem

Children with CP demonstrate a variety of defects in body structures, including decreased ROM, weakness, spasticity, poor balance and contractures (Gormley, 2001; Shepherd, 1995) that effect their postural control and movement patterns, hence interfering with the development of crucial functional tasks, such as walking (Gage, 2004). Children with CP walk with a less efficient gait pattern compared to their healthy peers (Cavgna, Franzetti, and Fuchimoto, 1983), which limits their ability to participate in typical activities for children their age (Rosenbaum et al., 2007; Sorsdahl, Moe-Nilssen, & Strand, 2008). Without proper intervention, these problems will aggravate with age and their condition will deteriorate (Jahnsen et al., 2003, 2004; Murphy et al., 1995), impacting all aspects of their lives, including education and employment (Donkervoort et al., 2007). Due to the deterioration of their health as they enter adulthood, children with CP will require the utilization of many medical services, hence increasing their medical expenses (CDC, 2004). Unfortunately, most of the current interventions lack supportive evidence (Anttila et al., 2008), appropriate dosages (Taylor, Dodd, & Damiano, 2005) or knowledge of the long-lasting effects (Anttila et al., 2008; Wiart, Darrah, & Kembhavi, 2008), and they are too labor-intensive (requiring more than one therapist) (Diaz, Gil, & Sanchez, 2011) to meet the needs of these children. Additionally, current approaches target only the Body Function and Structures level of the IFC (O'Neil et al., 2006). This could explain the lower rate of activity (Bjornson et al., 2007) and participation level (Orlin et al., 2010) among children with CP compared to their typical peers. It might also explain the increase in the demand for physical therapy services, since there is no improvement at the activity and participation levels, placing more financial burden on the families. Thus, there is a need to identify cost-effective, evidence-based interventions that could effectively and efficiently improve the deficits across the three domains of the ICF and fulfil the needs of children with CP and their families.

Purpose of the Study

The overall aim of this study is to investigate the extent to which robot-assisted task specific ankle training affects deficits across the three domains of ICF in children with CP.

Research Questions/Aims/Hypotheses

The International Classification of Functioning, Disability and Health (ICF) (WHO, 2015) was used as a framework to outline the research questions (Figure 2). The ICF model is a framework developed by the World Health Organization (WHO) to classify an individual's health and disability (WHO, 2015). ICF is subdivided into two components: (1) functioning and disability and (2) contextual components (Resnik & Plow, 2009; WHO, 2002). The functioning and disability aspect is further divided into three domains, including 1. Body Function and Structures, 2. Activity, and 3. Participation in peer leisure activities (WHO, 2001); contextual components include personal and environmental factors (Resnik & Plow, 2009; WHO, 2002). According to WHO (2001), body function is defined as "physiological functions of body systems," while body structures are defined as "anatomical parts of the body." The definition of activity is "the execution of a mobility task or action by an individual," and participation is considered "involvement in a life situation" (Jette, 2006; WHO, 2001). ICF is considered a comprehensive model because it accounts for an individual's structure and ability to function alone and with other members of society while also accounting for factors within the individual and the environment (Whiteneck, 2006).

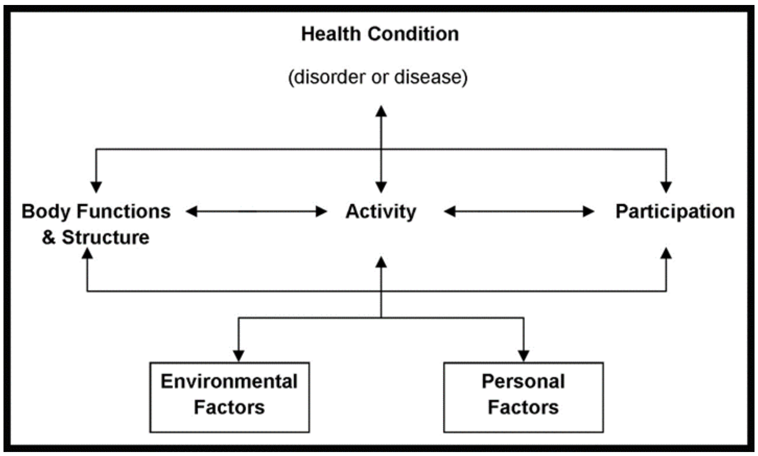


Figure 2. ICF model (WHO, 2015)

The overall research question for this study is "Can robot-assisted, task-specific ankle training improve deficits across the three domains of ICF in children with CP?". The subsidiary research questions are:

1. How can the robot-assisted, task-specific ankle training influence body function and structures in children with CP?
    - **<u>Specific Aim 1</u>:** To investigate the effectiveness of robot-assisted, task-specific ankle training (InMotion Technologies Anklebot) in improving body function and structures in children with CP.
        - **Sub-aim 1:** To test the hypothesis that robot-assisted, task-specific ankle training improves muscle strength, ROM, tone, balance, muscle

architecture, ankle control and coordination, and ankle performance in children with CP.

Hypothesis:

- After completing the training program children with CP will demonstrate bilateral increases in muscle strength and ROM of the lower extremity, decreases in spasticity in gastrocnemius and hamstring (bilaterally), increase of tibialis anterior (TA) thickness, increase in cross sectional area of Achilles tendon (AT), medial gastrocnemius muscles and TA, increase in pennate angle of TA, improvement in balance, increase in bilateral ankle control and performance when compared to the start of the program.

2. How can the robot-assisted, task-specific ankle training influence activity in children with CP?

- **Specific Aim 2**: To investigate the effectiveness of robot-assisted, task-specific ankle training (InMotion Technologies Anklebot) in improving activity deficits in children with CP.
    - **Sub-aim 2a:** To test the hypothesis that training improves spatiotemporal gait parameters including walking velocity, step length, cadence, single support duration and stance/swing duration after robot-assisted, task-specific ankle training.
    - **Sub-aim 2b:** To test the hypothesis that training improves the level of activity as measured by accelerometer (energy expenditure (EE) spent on light, moderate, and vigorous activities, total EE, number of steps, and total activity count (TAC)).

Hypothesis:

- After completing the training program children with CP will demonstrate increases in gait parameters including walking velocity, step length, cadence, single support duration and swing duration in addition to decrease in stance time when compared to the start of the program.
- After completing the training program children with CP will demonstrate increases in the level of activity as measured by accelerometer (EE spent on light, moderate, and vigorous activities, total EE, number of steps, and TAC) when compared to the start of the program.

3. How can the robot-assisted, task-specific ankle training influence participation in children with CP?

- **<u>Specific Aim 3</u>**: To test the hypothesis that robot-assisted, task-specific ankle training improves participation in children with CP.

  Hypothesis:

  - After completing the training program children with CP will demonstrate increases in participation level (especially among the physical activity categories including community life, mobility, personal care, housing and recreation) when compared to the start of the program.

Significance

There has been increased concern about rising healthcare costs, poor quality of services, and inconsistency in clinical practice. This study seeks to provide information about a potential cost-effective intervention that requires less manual support from the therapist, hence reducing patients' wait time to be seen by a therapist. This study proposes a clinically relevant intervention that relates changes in Body Function and Structures to a greater performance in activity and participation levels, in addition to introducing an approach that is built upon well-known theories, including motor learning, neuroplasticity and dynamic system theory. By introducing this theory-driven intervention, therapists could improve healthcare delivery and address the American Physical Therapy Association's (APTA) goals. APTA is an American professional organization that represents physical therapists, and by 2020, physical therapists will adapt theory-based clinical intervention (APTA, 2015). The study also addresses Healthy People 2020 goals. Healthy People 2020 is a set of national objectives aimed to improve Americans' health: "1) attain high-quality, longer lives free of preventable disease, disability, injury, and premature death; 2) achieve health equity, eliminate disparities, and improve the health of all groups; 3) promote quality of life, healthy development, and healthy behaviors across all life stages" (Healthy People, 2020).

This study focuses on people with disabilities, which is considered a priority for research according to the Agency for Healthcare Research and Quality (AHRQ) (AHRQ, 2012). This study also addresses the mission of the National Institutes of Health (NIH) "to seek fundamental knowledge about the nature and behavior of living systems and the application of that knowledge to enhance health, lengthen life, and reduce the burdens of illness and disability" (NIH, 2010). The proposed intervention "anklebot" is theorized to enhance the life of children with CP and to reduce the burden of disability on their families.

This study changed the typical approach to ambulatory rehabilitation for children with CP from proximal to distal manipulation. Gait abnormalities in children with CP are typically managed by a traditional approach that focuses on the proximal segment (hip) to affect the patient's gait by using braces (ankle foot orthosis). Patients are trained to walk wearing braces, which help to support the ligaments and limit excessive inversion (Hughes & Stetts, 1983; Laughman et al., 1980; Mack, 1982). However, braces restrict patients' abilities to participate freely in leisure activities, which is the rehabilitation's ultimate goal (Warken et al., 2015). Continuously wearing braces causes lesions to the skin, especially in children with diabetes and skin disorders (Steinau et al., 2011). Additionally, children will be dependent on using braces, and they will avoid using their own muscles to restrict unwanted movement such as excessive inversion, resulting in muscle atrophy in the ankle joint and a lack of the ankle's ability to block unwanted motion when they do not wear the braces (Greene & Wight, 1990; Hopper, McNair & Elliott, 1999; MacKean, Bell & Burnham, 1995). Hence, this reduces their quality of life (Steinau et al., 2011). Although braces are designed to support the ankle joint, they do not improve stride length or gait velocity in children with CP (Carlson et al., 1997). Lehmann et al. (1986) found that braces did not decrease foot slap occurrence in patients with a dropped foot. Moreover, wearing braces restricts the ankle range of motion (Alves et al., 1992; Anderson et al., 1995; Greene & Roland, 1989; Gross et al., 1992; Johnson, Veale, & McCarthy, 1994; Kimura et al., 1987; Löfvenberg & Karrholm, 1993; Vaes et al., 1998). This will affect the other joints on the lower limb, leading to changes in their movement pattern (DiStefano et al., 2008). Studies showed that ankle braces limit ankle motion in the sagittal plane (especially in dorsiflexion) during dynamic movements (DiStefano et al., 2008; McCaw & Cerullo, 1999), which is crucial for energy absorption (Norcross et al., 2013). Restricted dorsiflexors limit the ankle's ability to absorb its usual amount of energy, leading to a disturbance in the amount of energy absorbed by hip and knee joints (Devita & Skelly, 1992; McCaw & Cerullo, 1999). This will likely lead to injuries to their structures that are not well prepared for the extra energy that is absorbed. Waters & Mulroy (1999) provided evidence that a lack of ankle work due to impairment will lead to at least a 20% rise in energy expenditure. So by focusing on ankle training, this study examines a new approach to enhance gait, which is the ultimate goal for parents of children with CP (Beckung, Hagberg, Uldall, & Cans, 2008; Palisano, Hanna, Rosenbaum, & Tieman, 2010) hence decrease the risk of further secondary cardiovascular and musculoskeletal injuries related to lack of activity (Bartlett & Palisano, 2002; Bjornson, Belza, Kartin, Logsdon, & McLaughlin, 2007).

This study addresses two major knowledge gaps: (1) the efficacy of the new approach that focuses on treating the distal segment to improve gait and is based on skilled, defined movement of the ankle in children with CP; (2) the resultant outcome of robot-assisted, task-specific ankle training on strength, tone, ROM, balance, gait, ankle control, ankle performance, and muscle architecture for children with CP.

Theoretical Framework

The ICF is used as a framework to identify problems associated with CP, which is rooted at the structural level but is extended to function, activity and participation (Figure 2). In children with CP, the reciprocal relationships between ICF domains are seen as the various physical impairments, including muscle weakness, spasticity, restriction in ROM, lack of balance and coordination impacting the ability to walk in an efficient manner, hence limiting the child' ability to play and participate in leisure activity. Therefore, in this study we are proposing an intervention to facilitate improvements at the 1. Body

Function and Structures (ROM, muscle strength, etc) domain, as well as the 2. Activity (walking) and 3. Participation domains (engage in peer play). This will be accomplished by using the ICF model to guide our assessment through a variety of outcome measures to capture changes in the three domains of the ICF.

The theoretical foundation of "robot-assisted, task-specific ankle training" are built on several principles of motor learning, neuroplasticity, and dynamic system theory, which all fit in the ICF model.

Neuroplasticity

Neuroplasticity is the brain's ability to reorganize and alter its structure, connection, and function in response to stimuli (Cramer, 2011; Johnston, 2003). Research showed that the brain is not hardwired, but can adapt and change throughout the human lifespan (Nudo et al., 1997) during development, as well as in response to environmental changes, insults, and therapy, which open new therapies opportunities, including robotic therapy (Cramer, 2011; Nudo et al., 1997). Neuroplasticity takes different forms in adults and children. In adults following injury, the preserved brain structures will take over the function of the effected structure in a process called "reorganization of the brain connections", while in children, the lesion will alter the normal trajectories of ongoing development, leading those certain brain functions to develop in atypical locations (Staudt, 2010). In the last decade there have been increased interest about brain plasticity following training. Studies on neuroplasticity showed enlargement in the motor cortex map for the hand (Sawaki et al., 2008) and bilateral increases in sensorimotor grey matter (Gauthier et al., 2008) following constraint induced movement therapy (CIMT). Researches showed that plasticity and synapse formation occur at the later phase of training, while acquiring skills occur at the early phase of the training (Kleim et al., 2004). Unfortunately, the exact time of the map reorganization is unknown, which raises the question about the minimum period of training that causes brain plasticity. Kleim and Jones (2008) identified the principles of experience dependent plasticity, which allowed researchers to create more efficient therapeutic programs that drive neurological changes in the brain, resulting in permanent change in physical behavior. These principles include use it or lose it; use it and improve it; repetition matters; intensity matters; specificity; salience matters; age matters; time matters'; transference; and interference (Kleim & Jones, 2008).

The principle of "use it or lose it" has been investigated by several researchers, showing that synapses activated by training are preserved, while synapses that are not activated will fade or become pruned (Kleim & Jones, 2008). Several studies have shown that visual (Fifkova, 1969; Hubel & Wiesel, 1965) and auditory (Perier, Buyse, Lechat, & Stenuit, 1986) deprivation reduce the number of synapses in the cortex. It is evident that using your limbs will cause plasticity, but in order to further enhance plasticity, individuals need to engage in training, which is the base for the second principle of plasticity. A study conducted on monkeys with intact brains showed enlargement in the representation area of the digit in the motor cortex following fine digit movements training (Nudo et al., 1996). Similar results were found following skill training for rats with unilateral cortical lesions (Jones, Chu, Grande, & Gregory, 1999). Based on this principle and by engaging our patients in skilled training, we helped them create a new connection or change the current wiring to acquire or improve ability like walking.

The second principle of neuroplasticity is repetition. Repetition is needed to acquire the skill and make long-lasting change in behavior once the training is stopped (Monfils et al., 2005). Evidence has shown there is no increase in the strength (Monfils & Teskey, 2004) and number of synapses or change in movement representation in the brain (Kleim et al., 2002) following skilled reaching training until after a few days of exercise has taken place. Without enough repetition, patients will not gain skills that can last for longer periods of time that exceed the training session. In addition, evidence from an animal study showed that skilled reaching training using 400 repetitions daily increased the synapse number (Kleim et al., 2002), whereas low-dose training of 60 repetitions did not show any increase in synapse number (Luke, Allred, & Jones, 2004). Moreover, low-dose training not only caused no change in synapse number but also weakened the response of the synapse (Lisman & Spruston, 2005). Consequently, repetition to enhance plasticity should be done with caution to avoid overuse injury, especially during the vulnerable phase after an injury has occurred (Kleim & Jones, 2008). This is what makes robotics so valuable because of the highly repetitive training. When patients move their limbs repeatedly, this will help create and strengthen brain connection between neurons responsible for that movement, eventually leading to mastering the skill.

In addition to repetition, there are other task attributes, such as complexity, specificity, and engagement or motivation, which could enhance brain neuronal connections and cortical mapping (Cramer, 2011; Kleim & Jones, 2008). Fisher et al. (2001) found that rats trained in a more complex environment exhibited increased synaptogenesis in the motor cortex compared to rats trained in a simple environment. Also, the representation of the trained part was significantly altered after training (Fisher et al., 2001). Furthermore, tasks with higher complexity could induce bilateral sensorimotor area activation, even though it is a unilateral task (Gauthier et al., 2008; Kleim & Jones, 2008). In fact, the longer and more continuous the practice period, the more reassignment of the cortex occurred (Elbert et al., 1995). Overall, robotic training offers different games with varying difficulty levels, helping to cognitively engage patients and challenge them, leading to skill learning.

Specificity is another attribute for plasticity. Kleim et al. (2004) found that skill training led to synaptogenesis and map reorganization of movement representations, which does not occur in unskilled training. Similarly, Perez et al. (2004) presented that skilled ankle training improved corticospinal excitability compared to unskilled training. Plasticity is driven by meaningful tasks because patients' brains should attend to tasks to create lasting changes (Cramer, 2011); otherwise, they will not be motivated to complete the task or cognitively engage in training (Kleim & Jones, 2008). Evidence from a study using animals illustrated that animals trained with rewards have an increase in cortical representation (Weinberger, 2004). Consequently, offering specific training will help patients acquire the wanted skills instead of simply reiterating unskilled training.

Neuroplasticity is also sensitive to age, which means that children are more flexible to adaptation and have a greater capacity for plasticity (Chen et al., 2002b; Gardner et al., 1955; Staudt, 2010). Furthermore, children recover more quickly from injuries compared to adults because they are less experienced, which makes it easier to fill out their empty map. In contrast, adults learn new skills in the presence of an existing knowledge structure, leading to interference between these two types of knowledge, making change more difficult (Cramer, 2011; Johnston, 2003). Equally important, children have more connections compared to adults (Johnston et al., 2001; 2003), and at age two, children will have twice as many synapses as adults, which explains the greater capacity for brain plasticity (Gilmore et al., 2007; Nowakowski, 2006; Rakic, 2006). Moreover, from the age of two to early adulthood, plasticity will be enhanced (Johnston, 2003) prior to deteriorating due to a decrease in synaptogenesis (Greenough et al., 1986) and cortical reorganization (Coq & Xerri, 2001) because of normal aging. This explains the urgency to intervene early in life to enhance recovery and create a greater gain, as well as clarifies our sample selection of younger children because their brains tend to change and adapt more quickly than older brains.

Time is also a factor that impacts brain plasticity (Kleim & Jones, 2008). Evidence demonstrated that the sooner we introduce intervention following injury, the better results we achieve. This is evidenced in the study conducted by Biernaskie, Chernenko, and Corbett (2004), which submitted that a five-week training introduced five days after cerebral infarcts has better functional outcome and enhanced growth of dendrites compared to the same program delivered thirty days after cerebral infarcts. Hence, we focused on young children in this research due to their greater opportunity for brain rewiring.

Another principle of neuroplasticity is transference, where training-specific parts induce plasticity in different areas in the brain. Pascual-Leone et al. (1995) indicated that fine-digit task training increases corticospinal excitability and hand representation in the motor cortex. Plasticity could also interfere with learning, where maladaptive or negative plasticity, such as compensatory movement, could inhibit task learning. Additionally, Boyd and Winstein (2006) found that giving stroke patients specific instructions regarding tasks interferes with their learning ability, whereas explicit directions enhanced learning in healthy people. Therefore, therapists should pay attention to the changes that brain damage creates in neural response, as well as interference effects, to diminish any interference factors to neuroplasticity and learning (Kleim & Jones, 2008). Indeed, this was evident in our subjects with CP, who learned an easy way to walk with compensation, making it harder for us to teach them the proper way. By understanding this principle, we worked to remove any interference that impacted positive plasticity.

Motor Learning

Motor learning theory explains how individuals learn or relearn to perform movement (Shumway-Cook & Woollacott, 1995). Motor-learning principles indicate that short periods of intense training are needed to bring about changes in behavior measured after the retention period (Zwicker & Harris, 2009). These principles also emphasize the importance of feedback regarding learning ability (Zwicker & Harris, 2009). Another significant principle in motor learning is the type of practice—whole task versus part task—which can be determined based on the complexity of the task. Focusing on learning parts of the task is crucial, especially in the early stages of learning because it helps to facilitate skill acquisition of the whole task (Zwicker & Harris, 2009). Furthermore, studies have shown that including rest periods during practice repetitions (distributed practice) and introducing variable practice (e.g., walking on different surfaces rather than on the same surface) can result in improving retention compared to a single task of massed practice (Lee & Genovese, 1988; Shea & Kohl, 1991) as well as increase the transferability to other tasks of activity of daily living (ADL) (Krakauer, 2006). Researchers have shown that random practice is superior to blocked practice because it does not rely on memorizing and routinely repeating the movement, instead involving a high level of cognitive interference to problem solve each task (Krakauer, 2006; Li & Wright, 2000; Shea & Morgan, 1979; Wright, Black, Immink, Brueckner, & Magnuson, 2004). This principle does not interfere with the neuroplasticity principle of repetition. As much as repetition is important, it is also important to challenge the patient cognitively to enhance retention and transferability of the skills to another task. In summary, the previous evidence showed that these motor learning principles including short periods of part task which is intense, distributed, variable, random practice with feedback could influence learning in individuals with CP. Understanding these principles will help us to better incorporate these principles into our rehabilitation training program to augment it effectiveness.

Dynamic System Theory (DST)

Dynamic system theory (DST) describes the motor development of human beings across the life span (Effgen, 2012). This theory was built on the work of Nikolai Bernstein (1967) and that of many researchers who followed him (Adolph & Berger, 2006; Kelso, Holt, Kugler, & Turvey, 1980; Kelso & Tuller, 1984; Thelen, Kelso, & Fogel, 1987; Thelen & Smith, 1998). DST helps clinicians to understand the process of development of movement and change in the movement pattern (Smith & Thelen, 1993), which is organized by interaction of numerous sub-systems within the person, environment, and task (Thelen, 1989). Different components within individuals, including muscle strength, ankle control, and postural support, will interact (in addition to others) with environmental components such as gravity to create the most well-organized movement for each specific task (Thelen, 1989). The development of movement is nonlinear (Thelen, 1989), which means that the development does not occur at a steady rate, but rather each sub-system develops at its own rate. This development can be constrained by factors within individuals and the environment, which are called rate limiting factors (Howle, 2002). Any change in one sub-system will change the whole system, creating a new behavior (Smith & Thelen, 1993). So clinicians need to identify the rate limiting factors that limit the behavioral change and target them by intervention (Howle, 2002). I hypothesize that the lack of ankle dynamic control during gait is the most significant rate limiting factor that prevents children with CP from walking more efficiently and hence limits their participation. By training their ankles more efficiently, I expect children to improve their balance and walking patterns.

CHAPTER II. LITERATURE REVIEW

This chapter presents a comprehensive review of the literature on CP, current approaches, upper- and lower-limb assisted robotics therapy as well as that on ankle robotics and its challenges.

Cerebral Palsy

Children with cerebral palsy (CP) present with devastating issues that limit their ability across the three domains of the ICF. Based on the ICF model, children with CP experience limitation in body function including spasticity, muscle weakness, a decreased ROM, poor selective voluntary motor control, and contractures (Gormley, 2001; Shepherd, 1995). Due to these structural abnormalities, children with CP typically walk with an abnormal gait (Gage, 2004), which manifests with excessive hip flexion, in-toe walking (Wren, Rethlefsen, & Kay, 2005), a rigid knee during the swing phase (Sutherland and Davids, 1993; Wren, Rethlefsen, & Kay, 2005), hip internal rotation (Arnold & Delp, 2005), dropped foot (Wren, Rethlefsen, & Kay, 2005), and crouch gait (Bell et al., 2002; Wren, Rethlefsen, & Kay, 2005). This leads to limited walking abilities, including speed, energy cost, and balance (Van der Krogt, 2009). Children with limited walking abilities are often not able to play with their friends, restricting their social interactions (Huijing et al., 2013), which can further isolate them from society. Lack of peer engagement results in limited opportunities to develop skills and the competencies necessary to find a job and to live independently (Liptak, 2008). Engaging in play experience will give the children the opportunities to actively access and discover the world around them enhancing skill develop. If children miss these opportunities for routine peer interaction crucial skills will be delayed or not appear at all (Takata, 1974).

One study showed that children with disabilities are at risk for significant play deprivation (Brown & Gordon, 1987) that has a direct impact on self-efficacy and self-competence. Usually, children with CP engage in quiet play that is less varied than the play of children without disabilities; moreover, they play mostly with adults in limited active recreation activities (Brown & Gordon, 1987). So, focusing on ambulation and gait mechanic is crucial because it may be the key to transition into independency and efficiency in day-to-day activities. Additionally, as the children get older, their musculoskeletal problems will put extra stress on their bodies and put them at greater risk of decline (Jahnsen et al., 2003, 2004; Murphy et al, 1995). Children will suffer from chronic immobility, impaired bone health (osteoporosis), and mental health issues (disability-related depression) as they grow old. It has been found that 75% of individuals with CP stopped walking by age 25 due to fatigue and walking inefficiency (Murphy et al., 1995). Additionally, those individuals with poor gait function requiring the use of gait aids during childhood (GMFCS level III) are more likely to report a deterioration in walking ability or stop walking entirely when they reach adolescents (Jahnsen et al., 2003; Opheim, Jahnsen, Olsson, & Stangelle, 2009).

Due to their health deterioration as they enter adulthood, children with CP will maximize their utilization of medical services. The Centers for Disease Control and Prevention (2004) has estimated that the lifetime cost to care for an individual with CP is nearly $1 million. Age-related deterioration will limit the ability of individuals with CP to socially interact, live independently, and sustain employment. Evidence showed that the older age group (over 22 years) is less socially active than the younger group (15–18 years) (Stevenson et al., 1997). In a survey of adults with CP living in Denmark

(Michelsen et al., 2006), only 68% lived independently; in a survey from the Netherlands, Donkervoort et al. (2007) found that 20–30% of the adults with CP had restricted social participation, including taking responsibility, community living, leisure activities, and employment. Data show that people with disabilities are less likely to find jobs compared to their peers without disabilities (Michelsen et al., 2005; UNH, 2014). The employment rate among individuals with disabilities is 34% compared to that of individuals without disabilities, which is 74.2% (UNH, 2014). Employment has been consistently reported to be lower in adults who have CP than in comparable adults without disabilities (Michelsen et al., 2005). Thus, in order to reduce the risk of such declines due to aging, therapist should intervene early and aggressively (Jahnsen et al., 2003, 2004; Murphy et al, 1995).

Current Approaches

The ICF model (WHO, 2001) guides physical therapy interventions. This helps therapists to design interventions that target the three domains of ICF, including Body Function and Structures, activity, and participations (Rauch, Cieza, & Stucki, 2008). Evidence support early and aggressive intervention to maximize children's ability and minimize compensations and contractures (Harris, 1991; Low, 1980; Molnar, 1985; Shonkoff & Hauser-Cram, 1987). If therapists intervene early in the child's life, his or her GMFCS level will change; otherwise, it will be hard to change the level when the child gets older (Palisano et al 2007). Several therapeutic approaches such as neurodevelopmental therapy (NDT), Adeli Suit programs, ROM and passive stretching exercises have been used to treat children with CP in order to improve their walking pattern. Most of these current practices have failed to provide evidence of effectiveness or superiority either because (1) they involve multiple types of exercise, (2) targeting only at the level of the Body Function and Structures (O'Neil et al, 2006), (3) do not have a carry-on effect (Anttila et al., 2008), (4) deliver low doses of training, or (5) too labor intensive.

Therapies that contain multiple types of exercises such as NDT (Butler & Darrah, 2001), Adeli Suit programs (Bar-Haim et al., 2006), and conductive education (Odman & Oberg, 2006) lack evidence to support their effectiveness in the CP population due to lack of delivery standardization (Damiano, 2009). For example, approaches like ROM exercises target only at the level of Body Function and Structures (O'Neil et al, 2006) without attention to activity or participation, which is the ultimate goal of rehabilitation according to the III STEP conference recommendation (Damiano, 2006). Although these children will likely improve at the structural level, it is unlikely that significant improvement at the activity and participation levels will be achieved, which could question the efficacy of this intervention. Another common therapy is passive stretching, which has an immediate effect in improving spasticity, but evidence has failed to show any long-lasting benefit (Wiart, Darrah, & Kembhavi, 2008).

Although strength training is an effective approach, it needs to be continued regularly with very high doses to produce a significant change in the child's activity level (Taylor, Dodd, & Damiano, 2005). Most of the effective traditional therapies require more than one therapist to manually support the patient's legs during walking (Diaz, Gil, & Sanchez, 2011), reducing the number of patients seen by each therapist. This results in a long waiting list. Additionally, there are not enough certified therapists to effectively perform this intervention in a sustainable way; according to a new study from The Conference Board, there will be a shortage in physical therapists over the next decade

(APTA, 2014; TCB, 2014). This labor-intensive therapy will impose an economic burden on the healthcare system (Diaz, Gil, & Sanchez, 2011). Hence, more cost-effective interventions are needed.

Drawbacks of Current Approaches

The main features of efficient therapy for movement disorders seen in patients with CP are massed practice, functional relevance, and cognitive engagement of the patient (Charles, Wolf, Schneider, & Gordon, 2006; Damiano, 2006). Unfortunately, current approaches have failed to deliver the adequate intensity of training which is essential for skills development within the typical session due to limited training time (Fasoli et al., 2008). Highly intense and repetitive approaches that exceed therapist ability in one session (e.g. 1000 repetitions) are needed to improve motor function in populations with movement disorders.

Development of Robotics-Based Approaches

In an effort to augment the effect of physical therapy interventions, robotic technology has been developed for better functional training in the clinical environment (Basmajian et al., 1987; Burgar, Lum, Shor, & Van der Loos, 2000; Daly et al., 2005; Krebs, Hogan, Aisen, & Volpe, 1998; Krebs, Volpe, Aisen, & Hogan, 2000; Lum, Burgar, & Shor, 2004; Reinkensmeyer et al., 2000). Robotics is defined as ‘‘the application of electronic, computerized control systems to mechanical devices designed to perform human functions’’ (Kwakkel, Kollen, & Krebs, 2008). Rehabilitation robotics deliver high intensity, task-specific and controlled training that is highly engaging, which is consistent with the current effective rehabilitation paradigm for children with CP (Fasoli, Ladenheim, Mast, Krebs, 2012; Krebs et al., 2009). The interest in using robotic therapy has been increasing recently (Reinkensmeyer, Emken, Cramer, 2004; Riener, Nef, & Colombo, 2005), resulting in the development of many robotics devices for delivering training for upper and lower extremities, including an arm interactive therapy system (Díaz, Gil, & Sánchez, 2011), the Bi-Manu-Track (Basmajian et al., 1987), the Mirror-Image Motion Enabler (Burgar et al., 2000), treadmill gait trainers (Díaz, Gil, & Sánchez, 2011), foot-plate-based gait trainers (Díaz, Gil, & Sánchez, 2011), and ankle rehabilitation systems (Díaz, Gil, & Sánchez, 2011).

Advantages of Assisted Robotics Therapy

Assisted robotics therapy offers benefits to both the patients as well as the healthcare system. This can include delivering high repetition, task specific training that exceed therapist ability, objective measurement and visual feedback during intervention, motivating and engaging intervention, increase patients' compliance with the treatment, ability to be tailored to each patient's need, increase the efficiency of therapists, and it more cost- and time-efficient.

High-repetition

Robot-assisted training delivers the high-repetition movement needed to induce neuroplasticity (Nudo, 1997) which a therapist cannot deliver in a typical session. Evidence showed that treatment that focuses on repetitive practice of movements and functional activities is more effective than conventional treatment that focuses on teaching techniques and encouraging self-practice (Bütefisch, Hummelsheim, Denzler, & Mauritz, 1995; Kwakkel, Kollen, & Lindeman, 2004; Parry, Lincoln, & Vass, 1999). Another study supported the effectiveness of highly repetitive movement training facilitated by external forces applied to the limb in subjects with severe impairments (Feys et al., 1998).

Task Specificity

In addition to high repetition, task specificity is an important driver in an effective intervention (Van Peppen et al., 2004). Robot-assisted, task-specific training provides specific functional training to induce plasticity in the brain and cause permanent changes in behavior.

Measurement Tool

In traditional approaches, therapists wait until the next session to change a training approach. Robotic therapy, however, provides a measurement tool which helps therapists understand patients' performance and allows them to adjust therapeutic interventions in real time (Roberto et al., 2007). Moreover, the intrinsic feedback provided by robotics devices has been found to allow patients to process their performance and eventually develop a motor plan to correct themselves, rather than being offered a solution by the therapist (Muratori et al., 2013; Sidaway et al., 2012). A recent study showed that using visual and auditory feedback cues in training individuals with gait disorders due to CP could improve walking speed up to 25% and stride length up to 13%, compared to the group who were trained without feedback (Baram & Lenger, 2012).

Engaging and Motivating

Robot-assisted therapy is also engaging and highly motivating compared to traditional therapy; thus, it will increase patients' compliance with therapy. The level of engagement is greater among children due to their familiarity and interest in computer games and technology (Fasoli, Ladenheim, Mast, & Krebs, 2012).

Increase Patients' Compliance

Evidence showed that robot-assisted therapy increases patients' compliance with the treatment by introducing incentives such as games (Kwakkel, Kollen, & Krebs, 2008; Roberto et al., 2007).

Active Assisted (As Needed)

The newest designs of the robot-assisted devices allow them to be tailored to each patient's need (Roberto et al., 2007). They assist patients to perform a movement when they fail to move their body parts to reach a target in time and alter the amount of assistance they provide to patients based on their needs.

Work Efficiency

Rather than replacing clinicians, robotic therapy will increase the efficiency of their work. Instead of delivering limited-repetition, labor-intensive, manual intervention, therapists will play a more supervisory and guiding role. This will enhance their productivity without compromising the quality of care or the dosage of treatment (Krebs, Volpe, Aisen, & Hogan, 2000).

Cost- and Time-efficient

Another benefit of using certain robot-assisted devices is that they are more cost- and time-efficient than are transitional approaches. They can be used in a group therapy format or individually at home, which will reduce the cost of therapy (Daly et al., 2005). They can potentially reduce the expense of traveling to a physical therapy department and increase the time available for training, especially if they are used at home (Kwakkel et al., 2008).

Previous Work in Upper-Limb Robotics

Research has shown the benefits of implementing upper-extremity robotics in rehabilitation programs for adults with clinical conditions. Previous studies have primarily focused on conditions related to stroke (Kutner et al., 2010; Takahashi et al., 2008), spinal cord injuries (Cortes et al., 2013; Sledziewski, Schaaf, & Mount, 2012), Parkinson’s disease (Levy-Tzedek et al., 2007; Picelli et al., 2014) and multiple sclerosis (Carpinella et al., 2012). However, upper-extremity robotic rehab as begun to be used for children with CP (Fasoli et al., 2008; Frascarelli et al., 2009) because the clinical condition of CP results in movement disorders and activity limitations that are similar to what is seen in many of the adult conditions. It is expected that if studies of adults show significant results following robotics training, similar results will occur with children. This may be especially impactful when considering that a child’s brain possess a larger capacity to reorganize compared to adults, as they have more connections and synapses (Gilmore et al., 2007; Johnston et al., 2001; 2003; Nowakowski, 2006; Rakic, 2006), lack compensatory patterns, and the brain is less experienced and still developing, which make it more flexible to adaptation (Chen et al., 2002b; Gardner et al., 1955; Staudt, 2010).

Adult Studies

Most robotic therapy research has focused on adults and mostly with upper limb impairments following stroke, spinal cord injuries, Parkinson’s disease and multiple sclerosis (Aisen et al., 1997; Cortes et al., 2013; Picelli et al., 2014; Stein et al., 2004). Fasoli et al. (2003) reported improvement in muscle strength in the shoulder and elbow following upper-limb robotic therapy. Kahn et al. (2001) showed improvement in active joint movement excursion in the shoulder and elbow during post-robotic intervention. Research also reported gains in proximal arm strength, reduced motor impairment at the shoulder and elbow, and greater recovery in activity of daily living (ADL) functions in individuals with subacute stroke who received 25 hours of robotic therapy (Volpe et al., 2000). Takahashi et al. (2008) provided evidence that upper-limb robotic training enhanced hand motor function in individuals after a stroke. Another study showed improvement in activities, participation levels and quality of life in patients after a stroke (Kutner et al., 2010). These functional gains did not show up immediately after training, but they appeared during follow-up testing (Lum et al., 2002). Additionally, improvements were seen in both acute and chronic patients with stroke (Daly et al., 2005).

Similar results were seen in individuals with spinal cord injuries, including positive changes in active ROM, arm strength, perceived upper-limb function, self-care ability, and the smoothness of movements (Cortes et al., 2013; Sledziewski et al., 2012). Similarly, a number of studies showed significant improvement in arm function after robot-assisted arm training in patients with Parkinson’s disease (Levy-Tzedek et al., 2007; Picelli et al., 2014). Carpinella et al. (2012) found that upper-limb robotic therapy significantly decreased arm tremors and enhanced functional ability and arm kinematics for those with multiple sclerosis.

Children Studies

Since robotics therapy is a new approach for treating children with neuromuscular disorders, only a few studies have been conducted to investigate the feasibility and benefits of using this intervention with these children (Aharonsona & Krebs, 2012; Fasoli, Fragala-Pinkham, Hughes, Hogan, Krebs, Stein, 2008; Fluet et al., 2010; Frascarelli et al., 2009; Krebs et al., 2009). Recent studies showed significant gains in the quality of upper-limb skills, coordination, isometric strength of elbow extensors, smoothness of movements and upper-limb function, as well as a decrease in muscle tone of elbow flexors and pronators in children with moderate to severe CP years after their diagnosis (Fasoli, Fragala-Pinkham, Hughes, Hogan, Krebs, & Stein 2008; Frascarelli et al., 2009). A study by Fasoli et al. (2008) showed that robotic therapy is effective when combined with botulinum toxin type A (BTX-A) injections for improving upper-limb motor coordination, function, muscle tone and quality of motor performance in children with moderate CP. Several studies showed that robot-assisted therapy is a motivating and tolerable approach for children with moderate to severe hemiplegia due to CP (Fasoli, Fragala-Pinkham, Hughes, Hogan, Krebs, & Stein, 2008; Frascarelli et al., 2009; Krebs et al., 2009). A study by Wood et al. (2013) showed greater improvement in the ROM of forearm supination and wrist extension following upper-limb robotics training compared to conventional therapy. Upper limb robotic therapy combined with virtual reality resulted in greater improvement in the quality of upper-limb movement and reaching kinematics (movement smoothness and path length), as well as active ROM for shoulder abduction, flexion and forearm supination, than either intervention alone (Fluet et al., 2010). A randomize control trail showed that children with CP who received robot-assisted therapy combined with traditional therapy had more gains in smoothness of movement ($P < .01$) and manual dexterity ($P < .04$) scores compared to children who received traditional therapy alone (Gilliaux et al., 2015).

Krebs et al. (2012) found that robotics therapy not only causes significant improvement in trained movement that is sustained at follow-up assessments, but it transfers to other movements that were not trained. This indicates motor learning that exceeds the training effect. Qiu et al. (2010) found improvement in grip and pinch strength, kinematic measures in the form of movement time, path length and smoothness. The study also showed improvement in the overall upper-limb function as measured by the Melbourne Assessment of Unilateral Upper Limb Function (Qiu et al., 2010). Similar results were found in regard to kinematic measures in which robotics therapy decreased reach duration and path length, while improving movement smoothness and velocity (Qiu et al., 2011). Ladenheim et al., (2013) showed that children with CP or acquired brain injury who have a sequential presentation of targets have greater initial gains following robotics training, while the random group have greater retention at the six-month assessment. The proposed protocol in the reviewed studies is composed of 384-640 repetitive movements for the involved limb two to three times a week for a period of 6-8 weeks.

Previous Work in Lower-Limb Robotics

The results of previous research show that lower limb robotics training improves patients' walking ability similar to that of manual locomotor training; however, lower limb robotics required less clinicians' assistance and less discomfort to the therapist (Díaz, Gil, & Sánchez, 2011). Implementation of lower-extremity robotics has been studied with adults post-stroke (Roy et al., 2009; Zhang et al., 2013), multiple sclerosis (Goodman et al., 2014), and most recently with children with CP (Burdea et al., 2013; Cioi et al., 2011), which revealed improvements in ankle motor control seen in the increased targeting accuracy, speed, and smoothness of movements (SM) in the dorsiflexion–plantar flexion range and an overall improvement in walking speed (Banala, Kim, Agrawal, & Scholz, 2009). Girone (2000) showed improvement in ROM and ankle torque following Rutgers Ankle prototype robotics training, leading to improved walking patterns in patients with chronic ankle instability and hypomobility following fractures. Boian et al., (2002) reported improvements in ankle performance and walking patterns as a result of increased power generation and walking endurance following the use of the Rutgers ankle robot in individuals post stroke. Several studies have reported on the effectiveness of lower robotics in improving ankle muscle strength, ROM, joint stiffness, spasticity, motor control, balance, gait parameters, quality of life and game performance (Boian et al., 2003; Burdea et al., 2013; Cioi et al., 2011; Cordo et al., 2008; Deutsch et al., 2007; Homma et al., 2007; Mirelman et al., 2009; Selles, 2005; Wu, 2011). Very few studies have been conducted on children with CP, although they are the population most in need of this kind of engaging intervention.

Children Studies

Early evidence indicates that a robotic driven gait orthosis (DGO) is effective in improving gait speed and GMFM scores (Dimension D and E). It also emphasizes the importance of using augmented feedback during therapy to maximize improvements in walking speed, function, and endurance (Patritti et al., 2010). Children with bilateral spastic CP showed improvements in standing and walking, as measured by GMFM (Dimension D and E), after three weeks of robotic-assisted treadmill intervention. Improvements in the functional task of standing (Dimension D) were greater in children at GMFCS level III, while children at level I and II showed greater gains in walking

(Dimension E) scores (Borggraefe, Kiwull, Schaefer, Koerte, Blaschek, Meyer-Heim, & Heinen, 2010; Patritti et al, 2010). Meyer-Heim et al. (2009) showed that 5 weeks of driven gait orthosis training significantly improved gait speed and GMFM (Dimension D). Borggraefe et al. (2010) further examined the sustainability of the functional improvements gained following three weeks of robotic assisted treadmill training in children and adolescents with gait disorders after a follow-up period of six months. Following the three weeks of training, results showed significant improvement in GMFM (Dimension D and E), gait speed, and endurance, which was sustained at the 6 month follow-up assessment. Similarly, a randomized control trial by Smania et al. (2011) showed that repetitive locomotor training with an electromechanical gait trainer (Gait Trainer GT I) improved gait speed, step length, endurance, and kinematic measures of hip joint angles in ambulatory children with diplegic or tetraplegic CP. These improvements were persistent at the one month follow-up testing session and it was greater with the robotic group compared to control group who received only traditional therapy. Unfortunately, there were no significant changes in activity level as measured by the Functional Independence Measure (WeeFIM), which might be due to the short training period (10 training sessions). Training protocols across these studies were different.

Introducing Ankle Robotics and Its Challenges

Recent advances in robotic-based therapy have led to the invention of a new system called “robot-assisted, task-specific ankle trainers” (InMotion Technologies Anklebot) (Figure 3) that are designed to improve the function of the ankle joint through task-specific, robot-mediated activities.

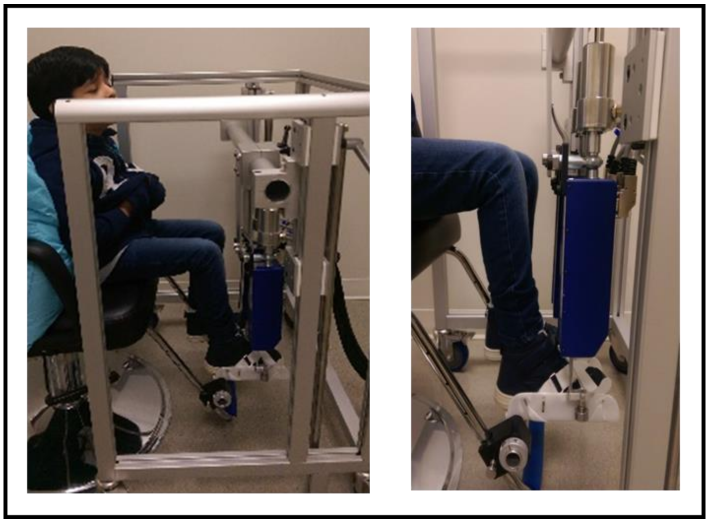


Figure 3. InMotion Technologies Anklebot, Watertown, MA

The robot-assisted, task-specific ankle trainer works through a three degrees of freedom computer-controlled device. It has one foot plate attached to an actuator, with two bars that go up and down with the child's ankle movement, which is connected to a video display. The participant's shoes are attached by straps to the footplate. A full description of the design and function of robot-assisted, task-specific ankle trainers is provided in chapter 3.

The Uniqueness of Ankle Robotics

There has been an increased interest in addressing problems distally by focusing on treating the ankle (Blaya & Herr, 2004; Roy et al., 2009) due to the importance of this joint, the severity of its involvement and its mechanical relationship with other joints.

The Importance of the Ankle/Foot

The importance of the ankle joint comes from its location at the distal segment of the body, where it provides a base of support that is essential to maintain balance (Cote et al., 2005). Additionally, due to its distinct location, it can sense changes in the surfaces and hence, alters its posture in response (Ferris and Farley, 1997; Ferris et al., 1998). Also, the uniqueness of tri-planar motion of the foot allows it to work as a shock absorber

(Roy et al., 2011) during pronation movement when the foot is dorsiflexed, everted, and abducted to unlock MidTarsalJoint (MTJ), providing the foot more mobility and enabling it for shock absorption. On the other hand, the tri-planar motion of supination (plantarflexion, inversion, and adduction) help lock the (MTJ), leading to a rigid foot that is necessary for forward propulsion during the gait cycle (Lark et al., 2003). During gait, the ankle joint performs the largest portion of work compared to the other joints (Winter, 1991). During a single stride, the plantar flexors provide 35-50% of mechanical power to allow for the forward thrust (Eng & Winter, 1995; Teixeira-Salmela et al., 2008; Umberger & Martin, 2007).

The Severity of Ankle Involvement

The ankle joint is more severally involved compared to the hip joint, making it logical to be targeted first for treatment (Gage, 2004). Dorsiflexors and plantar flexors are weaker in children with CP by about 30-35% compared to their normal peers (Burdea et al., 2013; Cioi et al., 2011). Recent results indicated that targeting these muscles with strengthening exercises could improve ankle function and overall gait patterns in children with CP (Dodd et al., 2003).

The biggest problem in the lower limb in children with CP is developed in the ankle joint and is called a “drop foot.” Drop foot occurs due to weakness in the dorsiflexors, which are responsible for elevating the foot in the early stance and swing phases (Roy et al., 2009). If left untreated, dorsiflexors deteriorate further as the child gets older (Hägglund & Wagner, 2011). Children with drop foot lack eccentric ankle control, which makes them slap their foot to the ground during heel strike and drag their toe during mid-swing, leading to an increased risk of falling and developing a compensatory gait pattern (Perry & Davids, 1992), including an anterior trunk lean. The child will lean forward to compensate for the weak dorsiflexors and knee extensors, bringing the center of mass in front of the knee, which may cause unsafe loading patterns on joints (Shankman & Manske, 2014, p. 229). In addition to dorsiflexion weakness, children with drop foot will have excessive inversion, leading to lateral instability in stance phase and toe contact in the swing phase (Roy et al., 2009). Overall, drop foot limits children's activity and participation levels, resulting in poor quality of life (Steinau et al., 2011).

Ankle Joint in Relation To Other Joints

Abnormalities in the ankle joint's structure have an effect on its mechanics as well as the mechanics of the knee and hip joints. The most common abnormality in the ankle seen in children with CP is weakness in the dorsiflexors and hyper-pronation due to foot drop, resulting in a long limb (Winters, Gage, & Hicks, 1987). When the foot pronates excessively, this pulls the foot into dorsiflexion, abduction, and eversion, which limit plantarflexion during the swing phase, leading to foot slapping at initial contact (Winters, Gage, & Hicks, 1987). The excessive pronation drag the tibia inward, followed by internal hip rotation and hip adduction due to the tibia's connection with the femur (Khamis & Yizhar, 2007). When the hip is internally rotated, this pushes the head of the femur posteriorly, resulting in anterior titling of the pelvis (Winters, Gage, & Hicks, 1987). When the pelvis tilts anteriorly, the leg shortens, and lordosis in the lumbar spine increases (Winters, Gage, & Hicks, 1987), leading to other compensations, such as scoliosis (McCaw, & Bates, 1991). Additionally, to further shorten the leg, the knee joint flexes during the heel strike, causing the hip to flex further to maintain the center of gravity above its base of support (Winters, Gage, & Hicks, 1987).

Studies on Ankle Robotics

Several feasibility studies have been conducted on normal children (Krebs et al., 2011) as well as children with lower limbs impairments including CP (Michmizos et al., 2015; Michmizos & Krebs, 2012; Rossi et al., 2013) and have found that the anklebot can be used easily and efficiently with these children (Krebs et al., 2011). Forrester et al. (2011) showed improvement in the effected ankle's motor control in the form of increased target success and faster and smoother movements following ankle robotics training. Improvements in gait speed and the duration of paretic single support are also seen, in addition to a decrease in the duration of double support. Forrester et al. (2014) suggested that ankle robotics therapy is well-tolerated during early subacute stroke hospitalization and improves ankle motor control and gait parameters (speed and symmetry). A study by Michmizos et al., (2012) showed that the games offered by ankelbot (the race, the soccer and the shipwreck games) are very engaging, which promotes motor learning.

Gap in Literature

Although the reviewed literature on robotic therapy was not organized by the three domains of the ICF, it shows robotic therapy benefits for improving deficits across these three domains in individuals with a variety of disabilities. Upper robotic modalities appear to be feasible in individuals with stroke, spinal cord injuries, Parkinson's disease, multiple sclerosis, and CP with the potential to promote improved proximal arm strength, coordination, active ROM, perceived upper-limb function, self-care ability, SM, ADL, and reduced motor impairment at the shoulder and elbow. Lower robotics is feasible in stroke, multiple sclerosis, and CP populations with the potential to enhance targeting accuracy, speed, and SM in the dorsiflexion–plantar flexion range, spasticity, muscle strength, joint stiffness, motor control, balance, quality of life and an overall improvement in walking speed. However, there have not been any studies specifically investigating robotic-assisted ankle trainers in children with CP to promote recovery in the three domains of the ICF. Therefore, additional research is needed to determine the effectiveness of the robot-assisted ankle trainer (Anklbot) on children with CP. Hence, this study was conducted to investigate the extent to which this robotic intervention impact deficits in pediatric rehabilitation.

CHAPTER III. METHODS

Indiana University's Office of Research Administration provided institutional review (Appendix 1), and informed consent (Appendix 2) and assent (Appendix 3) were collected for all participants prior to baseline.

Study Design

This study uses a quasi-experimental, single group repeated measures design with four time-testing points through a set training session/protocol (Figure 4). Participants underwent a 6-week program that included two 45-60 minute sessions per week, for a total of 12 sessions.

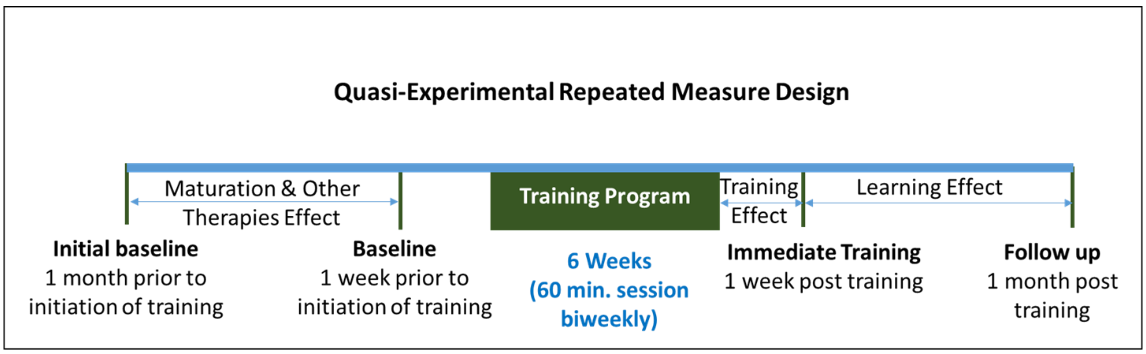


Figure 4. Study Design

Participants

A convenience sample of five children with CP were recruited by flyer (Appendix 4) from several clinics in and around Indianapolis (Appendix 5). A study overview is provided in Figure 5.

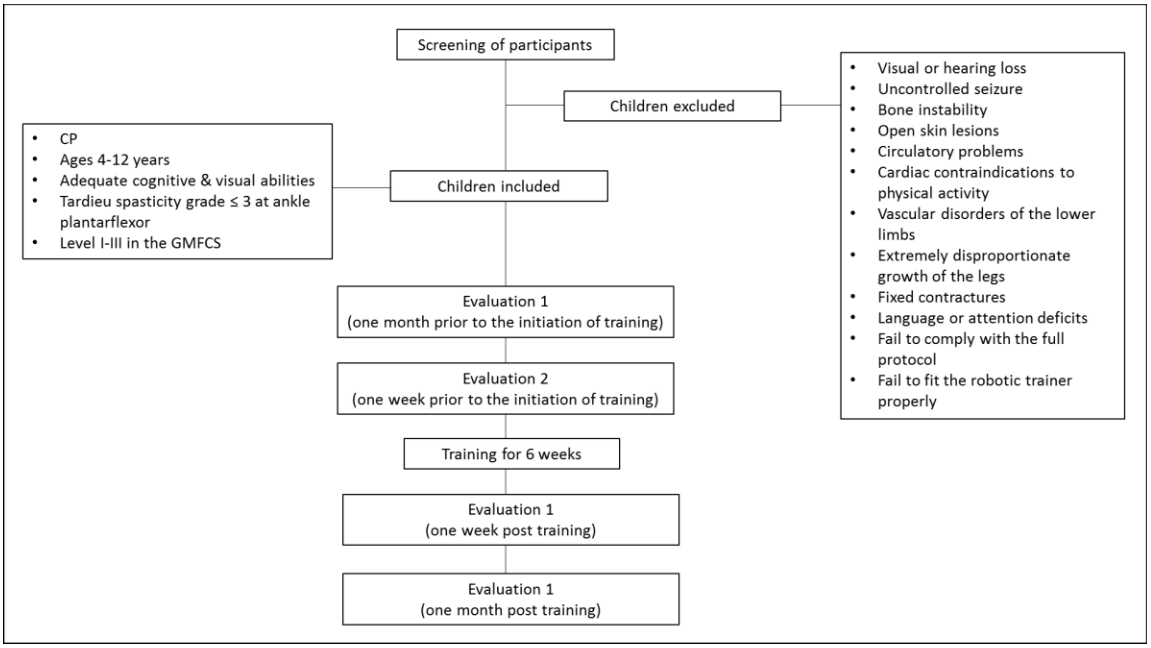


Figure 5. Study Overview

Inclusion criteria are as follows: diagnosis of CP, ages 4-12 years, adequate cognitive and visual abilities to understand the instructions, Tardieu spasticity grade less than or equal to three at ankle plantar flexor muscles, ability to independently stand and walk with or without assistance, and a classification of level I–III in the Gross Motor Function Classification System (GMFCS). Children with significant visual or hearing deficits, uncontrolled seizure, bone instability, open skin lesions, circulatory problems, cardiac contraindications to physical activity, extremely disproportionate growth of the legs, and fixed contractures were excluded from the study. Additionally, children who fail to comply with the full protocol (due to comprehension & attention deficits) or fit the robotic trainer properly were excluded.

Outcome Measurements

To answer the study's various questions, several physical parameters (e.g., strength, tone, ROM, balance, gait parameters, muscle architecture, selective motor control, ankle performance, and participation level), were collected at four time points through a set training session (Figure 4). Time point 1 values (initial) were collected 1 month prior to the initiation of training. Time point 2 values (traditional baseline) were collected 1 week prior to the initiation of training. Time point 3 values (immediately) were collected 1 week following the completion of training. Time point 4 values (follow up) were collected at a 1 month follow-up. Two physical therapy students (EF and KB) in addition to the main researcher (MH) collected the data. Outcome measures for (1) Body Function and Structures included Pediatric Balance Scale (PBS), Boyd and Graham selective motor control test, hand held dynamometer (HHD), goniometer, Tardieu Scale of spasticity, ultrasound, and robotic evaluation. Outcome measures for (2) Activity included gait mat analysis and accelerometer. Outcome measures for (3) Participation included Assessment of Life Habits for Children (LIFE-H for Children). Table 1 further outlines the outcome measures and their time points.

Table 1. Study's outcomes of interest, how they are measured and when measurement occurred.

What	How	When
Strength of • Plantarflexion / dorsiflexion • Eversion / inversion • Knee flexion/ extension • Hip flexion/ extension • Hip adduction/ abduction	HHD	Pre1, pre2, post1, & post2
Tone • Gastrocnemius • Hamstring	Tardieu Scale of spasticity	Pre1, pre2, post1, & post2
Active & passive ROM • Plantarflexion / dorsiflexion • Eversion / inversion • Knee flexion/ extension • Hip flexion/ extension • Hip adduction/ abduction	Goniometer	Pre1, pre2, post1, & post2
Balance	PBS	Pre1, pre2, post1, & post2
Ankle selective motor control	Boyd and Graham's selective motor control test	Pre1, pre2, post1, & post2
• Muscle thickness (MT)	Ultrasound	Pre2 & post2

What	How	When
• Cross-sectional area (CSA) • Pennation angle (PA)		
• Velocity • Step length • Cadence • Single support duration • Swing and stance duration	Gait mat analysis	Pre1, pre2, post1, & post2
• EE spent on light activity • EE spent on moderate activity • EE spent on vigorous activity • Total EE • Number of steps • TAC	Accelerometer	Pre2, post1, & post2
Participation	LIFE-H for Children	Pre 2 & post2
• Accuracy of movement • Movement smoothness	Robotic Evaluation	First & last training sessions

Body Function and Structures

*Balance (measured by Pediatric Balance Scale (PBS)).*The PBS was modified from Berg's balance scale to fit the pediatric population (Franjoine, Gunther, & Taylor, 2003). It consists of 14 items (Appendix 6) to assess functional balance in everyday activities in school-age children (5-15 years old) with mild to moderate motor impairments (Franjoine et al., 2003). Each of the PBS items is scored between 0 and 4 (where 0 indicates inability to perform the task, and 4 signals being perfectly able to perform the task); all scores were summed at the end, with the maximum score being 56 (perfect score) (Franjoine et al., 2003). The PBS is easy to administer and takes less than 20 minutes (Franjoine, Darr, Held, Kott, & Young, 2010). The evaluators assess each participant individually following the PBS test administration protocol described by Franjoine et al. (2003). The minimal detectable change (MDC) for the total score is 1.59 points, while the minimally clinically important difference (MCID) is 5.83 points for children with CP (Chen et al., 2013). The PBS has excellent concurrent validity with the

Gross Motor Function Measurement (GMFM-66) at baseline (r=0.92-0.95) and follow-up (r=0.89-0.91) in children with CP (Chen et al., 2013). However, it has adequate validity with the WeeFim at baseline (r=0.47-0.78) and follow-up (r=0.44-0.87) (Chen et al., 2013). It has excellent test-retest reliability (ICC=0.998) and excellent interrater reliability (ICC=0.997) in school-age children with mild to moderate motor impairments (Franjoine et al., 2003). The standardized response mean (SRM) of the PBS is 0.75 (Chen et al., 2013). The PBS was administered at all four testing sessions.

Ankle control (measured by Boyd and Graham Selective Motor Control Test). Boyd and Graham selective motor control test (Appendix 6) was used to assess the selective dorsiflexion of both ankles separately (Boyd and Graham, 1999). It has a five-point scale where 0 indicates no movement when asked to dorsiflex the ankle and 4 indicates dorsiflexion achieved using tibialis anterior without hip and knee flexion (Smits et al., 2010). The researchers assessed the participants in the long sitting position with hips flexed and knees comfortably extended (Figure 6). The child was asked to separately dorsiflex each foot.

This test has been used with children with CP (Lowing et al., 2010, Smits et al., 2010). The test showed moderate inter-rater reliability for ankle dorsiflexion left and right, weighted Kappas were 0.61 and 0.72 (Smits et al., 2010). The test-retest reliability was good (Lowing et al., 2010). Data from Boyd and Graham selective motor control test was collected at all four testing sessions.

A) Starting position B) Isolated movement

Figure 6. Boyd and Graham Selective Motor Control Test (Groenestijn & van Schie)

ROM (measured by Goniometer). Researchers measured active and passive joint ROM of the lower extremities. This included measuring hip (flexion/extension and abduction/adduction), knee (flexion/extension), and ankle (plantarflexion/dorsiflexion and eversion/inversion) ROM using a standard goniometer with participants in a lying and seated position (Gajdosik & Bohannon, 1987). Active ROM was measured first, followed by passive ROM. The participants' positions and the measurements taken by the goniometer (Hamilton, 2012) are reported in Table 2. Data from the goniometer were collected at all four testing sessions.

Table 2. Goniometer's administration to assess ROM

Movement		**Subject's Position**	**Goniometer's Position**	**Instruction**
Ankle	Plantarflexion	Prone with knee flexed 90^0	*Fulcrum:* center over lateral aspect of the lateral malleolus *Stationary arm:* align with the lateral midline of the fibula, projecting to the head of the fibula *Moving arm:* align parallel to the lateral aspect of the fifth metatarsal; inferior aspect of calcaneus	Point your toes downward as much as it can go
	Dorsiflexion	Prone with knee flexed 90^0	*Fulcrum:* center over lateral aspect of the lateral malleolus *Stationary arm:* align with the lateral midline of the fibula, projecting to the head of the fibula	Bring your toes up towards your face as high as it go

Movement		Subject's Position	Goniometer's Position	Instruction
			Moving arm: align parallel to the lateral aspect of the fifth metatarsal; inferior aspect of calcaneus	
Subtalar	Inversion	Short sitting	*Fulcrum:* over anterior aspect of ankle midway between malleoli *Stationary arm:* align with the anterior midline of lower leg projecting to the tibial tuberosity *Moving arm:* align with the anterior midline of the second metatarsal	Move your foot inward as far as it goes
	Eversion	Short sitting	*Fulcrum:* over anterior aspect of ankle midway between malleoli *Stationary arm:* align with the anterior midline of lower leg projecting to the tibial tuberosity *Moving arm:* align with the anterior midline of the second metatarsal	Move your foot outwards as far as it goes
Knee	Knee flexion	Supine	*Fulcrum:* center over the lateral epicondyle of the femur *Stationary arm:* align with the lateral midline of the femur, using the greater trochanter for reference *Moving arm:* align with the lateral midline of the fibula, projecting to the lateral malleolus and fibular head	Slide the heel of your foot along the bed up towards your bottom as far as you can go
	Knee extension	Supine with towel under ankle	*Fulcrum:* center over the lateral epicondyle of the femur *Stationary arm:* align with the lateral midline of the femur, using the greater trochanter for reference *Moving arm:* align with the lateral midline of the fibula, projecting to the lateral malleolus and fibular head	Push your knee down into the bed
Hip	Hip flexion	Supine	*Fulcrum:* over greater trochanter of the femur *Stationary arm:* align with the lateral midline of the pelvis *Moving arm:* align with the lateral midline of the femur projecting to lateral epicondyle	Bring your knee towards your chest as far as it goes
	Hip extension	Prone with pillow under abdomen	*Fulcrum:* over greater trochanter of the femur *Stationary arm:* align with the lateral midline of the pelvis *Moving arm:* align with the lateral midline of the femur projecting to lateral epicondyle	Keep your leg straight and move your whole leg above the bed as far as you can
	Hip abduction	Supine with toes point straight up (towards the ceiling)	*Fulcrum:* center over the anterior superior iliac spine (ASIS) of the limb being measured *Stationary arm:* align with an imaginary horizontal line extending from one ASIS to the other ASIS	Bring your leg out to my side as far as you can

Movement		Subject's Position	Goniometer's Position	Instruction
			Moving arm: align with the anterior midline of the femur projecting to the midline of the patella	
	Hip adduction	Supine with toes point straight up (towards the ceiling), scoot towards therapist and abduct your contralateral leg	*Fulcrum:* center over the anterior superior iliac spine (ASIS) of the limb being measured *Stationary arm:* align with an imaginary horizontal line extending from one ASIS to the other ASIS *Moving arm:* align with the anterior midline of the femur projecting to the midline of the patella	Bring your leg in towards the other leg as far as you can

Strength (measured by Hand Held Dynamometer (HHD)). For evaluating muscle strength, the evaluators used the MicroFet 2 HHD (Hoggan Health, Salt Lake City, UT, USA) (Figure 7) to measure the force generated by different muscle groups. This included the following muscle groups: ankle plantarflexors, dorsiflexors, evertors, invertors, knee flexors and extensors, hip flexors, hip extensors, hip abductors, and adductors.

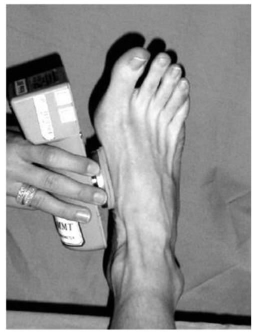
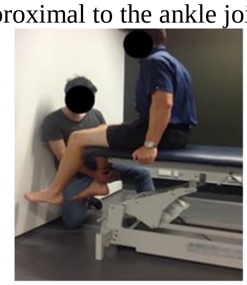
Figure 7. MicroFet 2 HHD (Hoggan Health, Salt Lake City, UT)

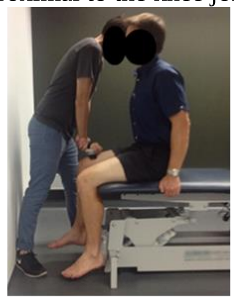
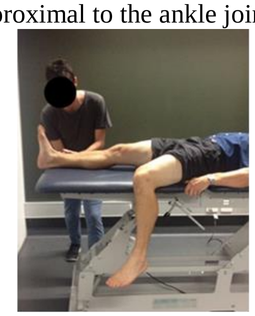
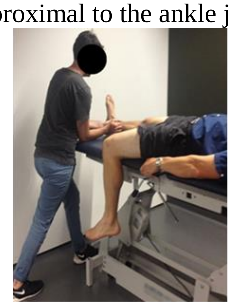
HHD records force production in pounds, kilograms, and newton. HHD is easy to administer, and is small, portable, and inexpensive (Chamorro, Armijo-Olivo, De la Fuente, Fuentes, & Chirosa, 2017). During the dynamometry measures, the participants were given clear instructions to perform maximum isometric contraction against the

HHD. The evaluators continuously encouraged the participants to produce maximum effort (Verschuren et al., 2008). The evaluators placed the dynamometer perpendicular to the tested muscle (Samosawala, Vaishali, & Kalyana, 2016). The tested muscles were assessed in the supine, prone, and sitting positions. Positioning and administration is further described in Table 3. The literature showed high intraclass correlation coefficients for test-retest reliability for isokinetic strength measurement in children with CP (Ayalon, Ben-Sira, Hutzler, & Gilad, 2000). Additionally, HHD showed moderate to excellent intrarater and interrater reliability in children with CP (Berry, Giuliani, & Damiano, 2004; Crompton, Galea, & Phillips, 2007; Dyball, Taylor, & Dodd, 2011; Verschuren et al., 2008). Data from the dynamometer were collected at all four testing sessions.

Table 3. Dynamometer positioning and administration

Movement	**Subject's and Dynamometer's Position**	
Ankle	Plantarflexion	Position: lying supine with the hips and knees extended. Dynamometer placed over the metatarsal heads on the sole of the foot.  (Mentiplay et al., 2015)
	Dorsiflexion	Position: lying supine with the ankle relaxed and hips and knees extended. Dynamometer placed over the metatarsal heads on the dorsum of the foot.  (Mentiplay et al., 2015)

Movement	Subject's and Dynamometer's Position	
Subtalar	Inversion	Position: lying Dynamometer placed over the medial aspect of the 1st metatarsal  (Burns et al., 2005)
	Eversion	Position: lying Dynamometer placed over the lateral aspect of the 5th metatarsal  (Spink, Fotoohabadi & Menz., 2010)
Knee	Knee flexion	Position: short sitting with hips and knees flexed at 90°. Dynamometer placed on the posterior aspect of the shank, proximal to the ankle joint.  (Mentiplay et al., 2015)
	Knee extension	Position: short sitting with hips and knees flexed at 90°. Dynamometer placed on the anterior aspect of the shank, proximal to the ankle joint.  (Mentiplay et al., 2015)

Movement	Subject's and Dynamometer's Position	
Hip	Hip flexion	Position: short sitting with hips and knees flexed at 90°. Dynamometer placed on the anterior aspect of the thigh, proximal to the knee joint.  (Mentiplay et al., 2015)
	Hip extension	Position: lying prone with the hip in neutral position and the knee in 90 degrees of flexion. The child can hold on to the sides of the table with both hands. Dynamometer placed 5 cm proximal to the knee joint line, at the posterior aspect of the thigh.  (Thorborg et al., 2010)
	Hip abduction	Position: lying supine with hips and knees extended. Dynamometer placed on the lateral aspect of the shank, proximal to the ankle joint.  (Mentiplay et al., 2015)
	Hip adduction	Position: lying supine with hips and knees extended. Dynamometer placed on the medial aspect of the shank, proximal to the ankle joint.  (Mentiplay et al., 2015)

Muscle tone (measured by Tardieu Scale of Spasticity of the Lower Extremities). This scale developed by Tardieu et al. (1954) (Appendix 6) measures muscle spasticity by evaluating the response of the muscle to passive stretch applied by the main researcher at Tardieu's two specified velocities, the slowest and the fastest possible speed (Gracies et al., 2000; Gracies et al., 2009). This scale has gone through multiple revisions (Haugh et al., 2006). The researchers administered this scale by positioning participants in supine position for testing gastrocnemius and hamstring spasticity. The researcher then passively moved the limb through a range at two velocities; as slow as possible (V1) and then as fast as possible (V3). At all velocities, the researchers assessed quality of muscle reaction (X) and angle of muscle reaction (Y). Quality of muscle reaction was measured on a 0-5 scale, where 0 is no resistance to passive ROM and 5 indicates an immobile joint. The angle of muscle reaction was measured with a hand-held goniometer. At the end of the assessment session, the Tardieu score was expressed as X/Y at each V value (Patrick & Ada, 2006). Tardieu scale (TS) was performed at the 4 testing sessions. Tardieu scale has been validated with individuals with CP, adults with severe brain injury or stroke, and adults with profound intellectual and multiple disabilities (PIMD) (Gracies et al., 2010; Mehrholz et al., 2005; RMD, 2012; Singh et al., 2011; Waninge et al., 2011). Fosang et al. (2003) found adequate to excellent correlation for the TS at hamstrings (ICC = 0.68-0.90), poor to excellent correlation of TS at gastroc (ICC = 0.38-0.90) and adequate to high correlation at hip adductors (ICC = 0.61-0.93) in children with CP. Mehrholz et al. (2005) found adequate intra-rater reliability (k = 0.65-0.87, ICC = .72- .65) for muscle groups tested; except shoulder external rotation (k = 0.53) for patients with severe brain injury. Paulis et al. (2011) compared the test–retest and inter-rater reliability of Tardieu

Scale scores measured with inertial sensors (IS) and goniometry and found excellent reliability for IS (ICC=0.76) and goniometry (ICC= 0.86) of elbow flexors in patients with stroke. In their study of individuals with hemiplegia after stroke, Ansari et al. (2008) found adequate inter-rater reliability for R2-R1 (ICC = 0.72) and adequate inter-rater reliability for TS quality (ICC = 0.74) and R1 (ICC = 0.74) and R2 (ICC = 0.56). Additionally, the results of Yam and Leung's (2006) study on children with CP showed poor to adequate reliability for Tardieu (ICC = 0.22-0.71) and poor to adequate: R1 (ICC = 0.37-0.71); R2 (ICC = 0.17-0.74; R2-R1 (ICC = 0.4-0.69). Patrick and Ada (2006) show strong construct validity of the Tardieu Scale as compared with an electromyographic measure of muscle reaction to fast stretch. The results showed excellent convergent validity (r = 0.86 elbow flexors; 0.62 ankle planter flexors). Additionally, the percentage of exact agreement of Tardieu and a laboratory measure of spasticity was 100% for elbow flexors and plantar flexors. Recently, the content validity of the Tardieu Scale and the Ashworth Scale was assessed in independently ambulating children with cerebral palsy (Alhusaini, 2010). The authors demonstrated that the TS was more effective than the Original Ashworth Scale in identifying the presence of spasticity, the presence of contracture and the severity of contracture. Neither scale was able to identify the severity of spasticity (Alhusaini, 2010). The TS has high level of sensitivity and specificity compared to the Ashworth Scale (Wallen et al., 2007). Data from Tardieu Scale of Spasticity were collected at all four testing sessions.

Muscle architecture (measured by Ultrasound). Ultrasound measurements were collected at the second pre-testing and at 1 month follow up by a qualified therapist (AP) using a portable diagnostic ultrasound (MyLab™ 25 Gold, Esaote, Florence, Italy) equipped with a 10-18 MHz real-time linear transducer. The sonographer (AP) was blinded to the training protocol and clinical findings. The ultrasound images obtained were the cross-sectional area (CSA) of the Achilles tendon (AT) and medial gastrocnemius muscles and for the tibialis anterior (TA) muscle both CSA and muscle thickness. All measurements were performed bilaterally and two images were obtained in each view. The assessment was made with participants in the supine and prone positions, which will later be explained in detail in relation to the muscles that have been tested. During testing, participants' limbs were exposed from mid-thigh to apply the gel to the skin. In addition, the gel was applied to the head of the transducer to improve the image quality. Then CSA, MT, and PA were measured for all participants using the ultrasound imaging software. CSA is defined as "the area surrounded by the upper muscular fascia, the lower muscular fascia, and the intramuscular septum" (da Matta & de Oliveira, 2012). MT is defined as "the distance between two fascias" (Strasser, Draskovits, Praschak, Quittan, & Graf, 2013). PA is defined as "an angle between muscle fascicles and the muscle line of action" (Ema, Akagi, Wakahara, & Kawakami, 2016) (Figure 8). The literature showed that using ultrasound to measure the CSA and MT provides excellent reliability in assessing children and adolescents with CP (Mohagheghi et al., 2008; Moreau, Teefey, & Damiano, 2009). Additionally, the literature showed high interrater and intrarater reliability (all ICC values above .90) of the ultrasound to measure muscle thickness (Temes et al., 2014). On average, the image capturing took 15 minutes and image analysis 20 minutes per subject.

PA is the black arc between the muscle fiber (blue line) and tendon (red line) (Sopher, Amis, Davies, & Jeffers, 2017)

Figure 8. An example of how to estimate PA

Achilles Tendon. Participants were in prone position in 10° ankle plantarflexion of the ankle and the foot extending off the end of the bed to promote relaxation (Figure 9) (Dong & Fessell, 2009). For tendon CSA the ultrasound transducer was positioned perpendicular to the tendon to acquire tomographic images at 2, 4 and 6 cm proximal to the tendon insertion.

Figure 9. Positioning for scanning the
Achilles tendon (Backhaus et al., 2001)

Tibialis Anterior. Participants were in the supine position with knee flexed 45° (Figure 10) (Varghese, & Bianchi, 2014). For TA the ultrasound transducer was oriented in the sagittal plane perpendicular to the skin to acquire tomographic images for muscle thickness and PA. Bilateral cross-sectional images were taken with the probe oriented in the transverse plane perpendicular to the skin.

Figure 10. Positioning for scanning the
tibialis anterior (Backhaus et al., 2001)

Medial Gastrocnemius. Participants were examined in the prone position with both knees in slight flexion and the legs resting on a pillow or towel, placed under the anterior aspect of both legs (Figure 11) (Bianchi, Martinoli, Abdelwahab, Derchi, & Damiani, 1998). Transverse sonograms of both medial gastrocnemius muscles were obtained.

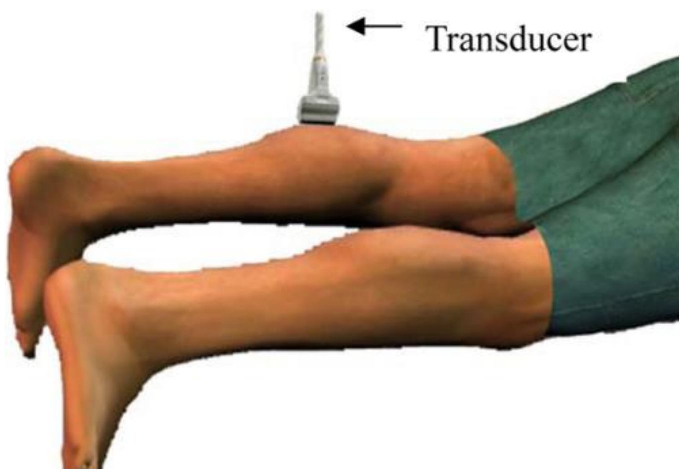


Figure 11. Positioning for scanning the medial
gastrocnemius (Chen et al., 2009)

Ankle Performance (measured by Robotic). Robotic Evaluation (Forrester et al., 2011) is outcome testing internal to the robot-assisted ankle trainers to measure participants' performance based on the initiation of movement (how often did the robot initiate the motion); accuracy (the average number of successful passages); robot power (how much moving power the robot provided rather than the patient); dwell time (how much time was the patient waiting near the target); and movement smoothness (how rough was the patient's motion) (Figure 12).

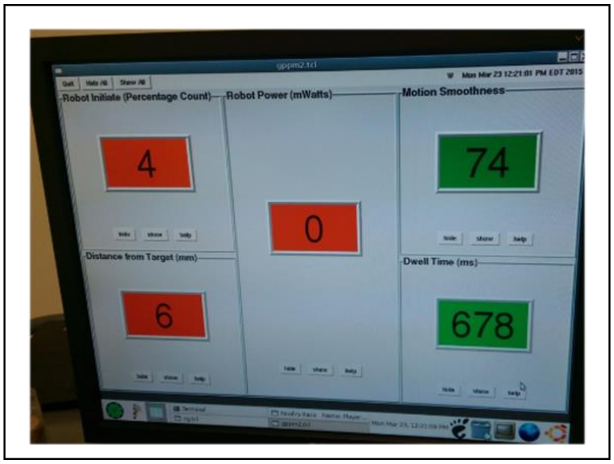


Figure 12. Graphic visualization of the Child's performance

For the purpose of this study we only collected data on accuracy and smoothness. Robotic evaluation assessed the participants' performance after each set of 44 repetitions (Appendix 7). Data from robotic evaluation were collected at the first and last training sessions.

Activity

Gait (measured by Gait Mat Analysis). Gait analysis (Berman et al., 1987) was performed by using a gait mat (ProtoKinetics LLC, Havertown, PA, USA) to capture spatial-temporal parameters during clinical walking tests (see Figure 13). This mat consists of a long walking surface that measures velocity, step length, cadence, single support time, and stance and swing time during walking.

Figure 13. The Zeno Walkway by ProtoKinetics

This system uses PKMAS software (ProtoKinetics LLC, Havertown, PA, USA) for video and data acquisition and processing. Three trials of walking without braces with or without an assistive device were conducted on the Protokinetics Zeno Walkway mat. Participants were asked to walk at a comfortable speed back and forth across the mat for three trials. Data from the gait mat was collected at all four testing sessions.

Activity counts (measured by Accelerometer). The actical accelerometer (Philips Respironics, Bend, Oregon) (Figure 14) was given to participants and worn at the baseline testing session, then returned to the lab at the 1-month follow-up assessment session. The actical accelerometers were set to record activity in 60-s epochs.

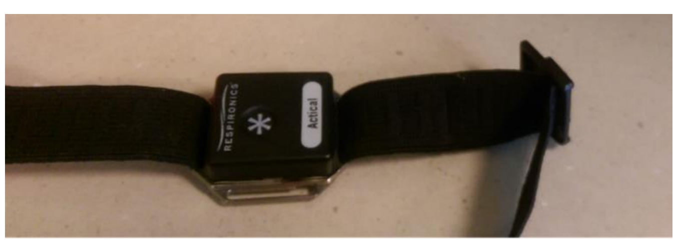


Figure 14. Actical accelerometer (Philips respironics, Bend, Oregon)

The accelerometer measured EE spent on light, moderate, and vigorous activities; total EE; number of steps; and TAC throughout the week. Data from the accelerometer were collected at one week pre-training, one week post-training, and one month follow up. At each of the three time points, children wore the actical from morning until night on their ankle for five days. Although the literature did not show consensus on the duration of acceptable monitoring periods (Trost, Pate, Freedson, Sallis, & Taylor, 2000), the monitoring period of our study was very similar in length to monitoring periods in other studies (Butte, Puyau, Adolph, Vohra, & Zakeri, 2007; Jago, Anderson, Baranowski, & Watson, 2005). The children were advised to take the actical off at night and when showering because it is not water resistant (Puyau, Adolph, Vohra, & Butte, 2002; Ward, Evenson, Vaughn, Rodgers, & Troiano, 2005). At the end of the last three testing sessions, the actical data were downloaded and saved to a desktop computer at the IU Neuroscience Center for subsequent analysis. The accelerometer has good reliability with an intraclass correlation of 0.99 (Esliger & Tremblay, 2006).

Participation

Life Habits (measured by Assessment of Life Habits for Children (LIFE-H for Children) short form). LIFE-H is a self-report questionnaire (Appendix 8) that is designed to assess one's accomplishment in life habits (Fougeyrollas et al., 1998). According to Jarvis and Hey (1984), life habits are "those habits that ensure the survival and development of a person in society throughout his or her life." LIFE-H forms are designed for the following three age groups: children 0-4 years old, children 5-12 years old and the general form (for teenagers, adults, and seniors). There are two versions (short and long) of the general form and the form for children 5-12 years old (Quebec, 2007). The LIFE-H short form for children evaluates children on 62 life habits across 12 domains based on their perception of the degree of difficulty and the type of required assistance (Fougeyrollas et al., 1998; Quebec, 2007). These domains include nutrition, fitness, personal care, communication, housing, mobility, responsibilities, interpersonal relationships, community life, education, employment and recreation. The participants use a five point ordinal scale to report the degree of difficulty and a four point ordinal scale to report the nature of assistance required to achieve each life habit. Data from LIFE-H for Children were collected at the second pre-testing and the second post-testing sessions. LIFE-H has been validated with individuals with a variety of impairments, including CP (Sakzewski et al., 2007), stroke (Desrosiers et al., 2003), spinal cord injury (Noonan et al., 2009) and traumatic brain injury (Noreau et al., 2004). Test-retest reliability is adequate for the LIFE-H short form (ICC=0.67) for children and excellent for the LIFE-H long form (ICC = 0.80) for children (Noreau et al., 2002). The LIFE-H long form for children has a high intra-rater reliability with an ICC of 0.78 or higher (Quebec, 2007). The LIFE-H personal care and housing dimensions have a strong correlation with the Pediatric Evaluation of Disability Inventory (PEDI) self-care and mobility dimensions ($0.79<r <0.88$), while LIFE-H communication and responsibility dimensions have a strong correlation with PEDI social function ($r=0.80$/ $r=0.81$) (Quebec, 2007). Data from the LIFE-H questionnaire was collected at the second pre and post testing session.

Description of The Ankle Robot "Anklebot"

The anklebot is a backdrivable robot with low intrinsic mechanical impedance that has three degrees of freedom (DOF): dorsiflexion/plantarflexion, inversion/eversion and internal/external rotation. It allows “25^0 of dorsiflexion, 45^0 of plantarflexion, 25^0 of inversion, 15^0 of eversion, and 15 degrees of internal or external rotation” (Michmizos & Krebs, 2012; Roy et al., 2009). The ankelbot gives active assistance in dorsiflexion/plantar flexion and inversion/eversion, and a passive DOF for internal/external rotation (Michmizos & Krebs, 2012; Roy et al., 2009). It consists of one foot plate that has two Velcro straps, and it is connected to two linear actuators by quick-release locking clamps. If these actuators move in the same direction, a dorsiflexion/plantarflexion torque is applied at the ankle; if they move in opposite directions, an inversion/eversion torque is applied at the ankle (Michmizos & Krebs, 2012; Roy et al., 2009). The actuators are attached to the computer display (Michmizos & Krebs, 2012; Roy et al., 2009) (Figure 3). Anklebot weighs less than 3.6 kg (Roy et al., 2009). It takes the therapist less than two minutes to set up the device. Anklebot is highly valid and reliable (in the unmodified version) with standard error of the estimate ≤1° in both DOFs of planter-dorsi flexion/ inversion-eversion, and the error in torque estimation is <1 Nm (Forrester et al., 2013).

Intervention

The intervention took place at Neurorehabilitation and Robotics lab at the Indiana University Health Neuroscience Center and was led by the main researcher (MH). Two physical therapy students (EF and KB) assisted participants during testing and intervention sessions under the supervision of the main researcher (MH).

At the beginning of each training session, each child took a seat facing a screen in a padded adjustable chair and was secured with a safety hardness if needed. The child’s foot was placed in the footplate and secured with two straps over the metatarsals. The device was sized to fit the child, allowing the child to move his or her ankles through the available range of motion (Figure 3). Both feet were trained separately, regardless of deficit. Since the walking task involves the use of both feet, bilateral training is necessary to get control over both feet. Once secured, the robot was calibrated, so it produces movements customized to each specific child. The child then participated in the intervention session consisting of a total of 528 movements for each ankle (Table 4).

Table 4. Anklebot Protocol: The 3 games that children played and the repetitive movements associated with each game.

Game	Plantarflexion/Dorsiflexion	Inversion/Eversion	Combination
Race	44 X 3= 132	44	44
Shipwreck	44 X 3= 132	44	
Soccer			44 X 3 = 132

Participants played three different video games (Figure 15) that requires repetitive dorsiflexion, plantarflexion, and eversion and inversion of the ankle by moving a screen cursor "up or down" in addition to "inside or outside". The participants were unassisted while automatically tracking their performance; however, if they fail to move their ankles to reach a target in time, the robot will provide assistive ankle torques, which is suitable to each child's need. Participants received continuous visual and oral feedback during each session about their performance from the investigators and the robot-assisted ankle trainers. Participants were given rest periods as needed. During the study, participants continued their usual physical and occupation therapy without any change.

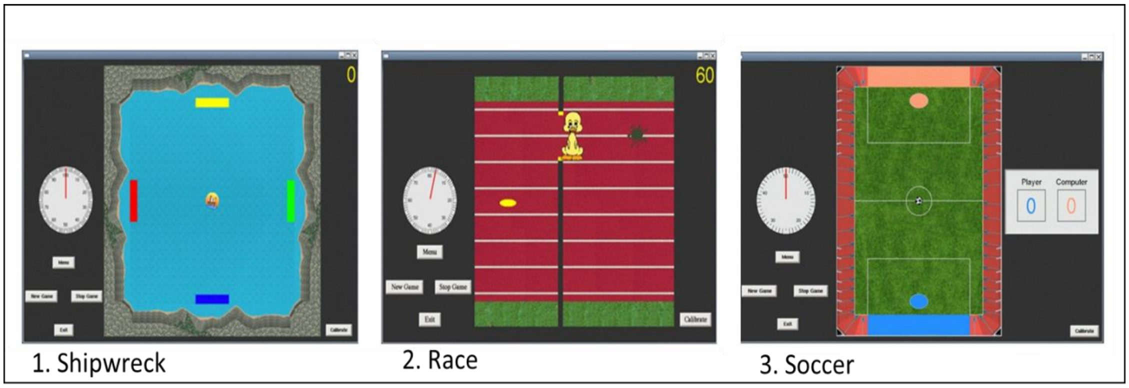


Figure 15. The anklebot video games (Michmizos & Krebs, 2012)

Data Collection

Prescreening for eligibility was completed through telephone conversations with the children's parents, who have been previously referred to the robotics lab to ensure they met the inclusion criteria (Appendix 9). Following prescreening, potential participants were scheduled for the testing sessions and were asked to complete the informed consent and assent forms at the robotics lab (Appendix 2 & 3). All children enrolled in the study (n =5) participated in identical testing sessions and interventions at the robotics lab. During the first testing session, one trained researcher and two physical therapy students collected the children's medical history by interviewing their parents and assessed the children's gross motor function level using the GMFCS.

Data Management

All participants' data were coded to ensure no loss of confidentiality during dissemination of any data. Participants' research records were stored in locked cabinets and secure computer files at the IU Health and Neurorehabilitation and robotic lab which was accessed only by researchers involved with the study and physical therapy students trained to provide treatment within the robotics lab.

Data Analysis

All statistical analyses were performed by using SPSS statistical procedures version 24, accessed via IUAnyWare Citrix application access portal. Descriptive statistics—means, standard deviations and percentage—were used to summarize the characteristics of the participants. Repeated measures analysis of variance (ANOVA) were used to compare mean scores of the different parameters due to the complexity of the design (multiple time points). Using a repeated measures ANOVA allowed the researcher to compare time points more simply under the assumption that the data would be firmly normal if a larger study was conducted. The repeated measures ANOVA was used with all outcome measures, including those that were only measured at 2 time points (i.e., ultrasound, questionnaire, and robotic data) for consistency. Table 5 further outlines the study aims in relation to the type of statistical tests. The research set the significance level at $\alpha = 0.05$. Due to the preliminary nature of the data, a trend is a p value between 0.05-0.10.

Table 5. Description of the study aims and the statistical tests

#	Aim	Outcome	Measure	Statistical test
Aim 1	To test the hypothesis that robot-assisted, task-specific ankle training improves muscle strength, ROM, tone, balance, muscle architecture, ankle control, and ankle performance in children with CP.	Strength	HHD	Repeated measure ANOVA to investigate the changes in mean scores over different time points
		Tone	Tardieu Scale of spasticity	
		ROM	Goniometry	
		Balance	PBS	
		• Accuracy • Movement smoothness	Robotic evaluation	
		• CSA • MT • PA	Ultrasound	
		Ankle control	Boyd and Graham's selective motor control test	

#	Aim	Outcome	Measure	Statistical test
Sub-aim 2 a	To test the hypothesis that training has a positive impact on spatiotemporal gait parameters after robot-assisted, task-specific ankle training.	• Walking speed • Step length • Cadence • Single support time • Swing and stance time	Gait mat	
Sub-aim 2 b	To test the hypothesis that training has a positive impact on the level of activity as measured by accelerometer (number of steps, total EE, EE spent on light/moderate/vigorous activity, and TAC).	• EE spent on light activity • EE spent on moderate activity • EE spent on vigorous activity • Total EE • Number of steps • TAC	Accelerometer	
Aim 3	To test the hypothesis that robot-assisted, task-specific ankle training improves participation in children with CP.	Participation	LIFE-H for Children	

CHAPTER IV. RESULTS

This chapter presents the results of the research study. It provides a description of the study participants and the variables considered throughout the study. A comprehensive description of the effect of the task-specific ankle training on the three domains of ICF for children with CP will be presented. The results were reported by ICF domains (Body Function and Structures, activity and participation) within each of these domains, repeated measure ANOVA results were reported followed by post hoc analysis to determine significant within different time points.

Characteristics of the Study Sample

During the period of March 15, 2016, to May 25, 2017, a total of 12 children were referred by physicians and physical therapists (in and around Indianapolis) to the neuroscience center as potential participants. Of the 12 children identified as potential participants, three did not meet the inclusion/exclusion criteria, and nine met all inclusion/exclusion criteria and were invited to participate in the study. Only three children refused to participate after being invited to the study, due to time and family commitments. One child was withdrawn from the study during the second evaluation phase due to scheduling conflicts (Figure 16).

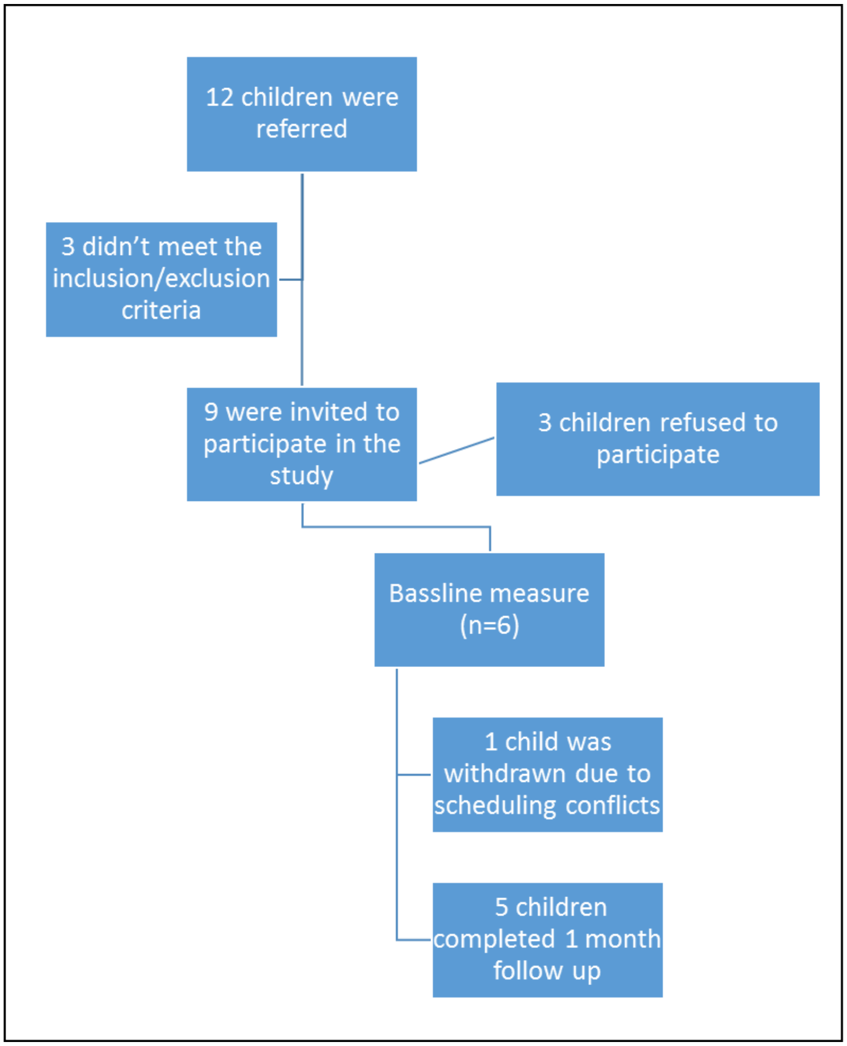


Figure 16. Flow diagram for subject in this study

The sample consisted of four boys and one girl, ranging from age 4–11, with a diagnosis of CP. All subjects were bilaterally involved but the majority of subjects (80%, or four out of five) had right-side hemiparesis, and 80% of the sample (four out of five) was at GMFCS level I. Participant characteristics are shown in Table 6. Only data from participants who did not drop out (n = 5) were included in the analysis.

Table 6. Participants' characteristics

Participant	**Age**	**Sex**	**Diagnosis**	**GMFCS**	**Impairments**	**Current use of orthosis**
1	5	Male	CP	III	R hemiplegia	Y
2	9	Female	CP	I	R hemiplegia	Y
3	11	Male	CP	I	Diplegia	N
4	10	Male	CP	I	L hemiplegia	Y
5	4	Male	CP	I	R hemiplegia	Y

Data Findings

The ICF model was used to guide data collection and answer research questions.

1. Body Function and Structures Level

The results revealed that, for outcome measures in Body Function and Structures level, there were no significant differences found between pretest one (initial) and two (baseline).

Strength

Strength: Ankle Dorsiflexors. Data from the hand-held dynamometer were analyzed for all four-time points. The results indicated that the mean muscle strength of the less-affected ankle dorsiflexors significantly increased from 6.84 N± 1.95 N to 14.24 N± 3.34 N at 1 month follow up, a 112% improvement (Table 7 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.06, 4.24) = 45.23$, $p = .002$). Post hoc tests using the Bonferroni correction revealed statistically significant differences on mean score between initial and immediate training ($p = .029$), initial and follow up ($p=.013$), baseline and immediate training ($p = .017$), baseline and follow up ($p = .007$), and immediate training and follow up ($p = .006$). No statistically significant difference was found between initial and baseline ($p = 1$) (Table 8 & Figure 18). The results show that the mean muscle strength of the more-affected ankle dorsiflexors significantly increased from 5.82 N± 2.32 N to 12.08 N± 3.34 N at 1 month follow up, a 124% improvement (Table 7 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.31, 5.26) = 25.20, p = .003). Post hoc tests using the Bonferroni correction revealed a statistically significant difference on mean score between initial and follow up (p=.010) and baseline and follow up (p = .014). No statistically significant changes were seen between initial and baseline (p = .476), initial and immediate training (p = .066), baseline and immediate training (p = .098), immediate training and follow up (p = 1) (Table 8 & Figure 18).

Table 7. Mean ± SD ankle dorsiflexion strength (N) changes prior to and after training.

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) ankle DF	6.52± 1.56	6.84± 1.95	13.16± 3.46	14.24± 3.34	45.23	1.06, 4.24	.002*
(MA) ankle DF	4.56± 1.40	5.82± 2.32	11.46± 4.67	12.08± 3.34	25.20	1.31, 5.26	.003*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 8. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
(LA) ankle DF	1	.029*	.013*	.017*	.007*	.006*
(MA) ankle DF	.476	.066	.010*	.098	.014*	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Strength: Ankle Evertors. The mean score of less-affected ankle evertors statistically increased from 4.90 N± .836 N to 11.32 N± 2.33 N at 1 month follow up, improving by 132% (Table 9 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.11, 4.46) = 35.82, p = .003). Post hoc tests using the Bonferroni correction revealed statistically significant differences on mean score between initial and immediate training (p = .039), initial and follow up (p=.006), baseline and immediate training (p = .046) and baseline and follow up (p = .009). No statistically significant difference was found between initial and baseline (p = 1) and immediate training and follow up (p = 1) (Table 10 & Figure 18). The mean score of more-affected ankle evertors increased from 4.20 N± .900 N to 9.50 N± 2.71 N at 1 month follow up, a 136% improvement (Table 9 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.10, 4.41) = 20.31, p = .008). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training (p = .044) and initial and follow up (p=.040). No statistically significant differences were found between initial and baseline (p = 1), baseline and immediate training (p = .085), baseline and follow up (p = .086), and immediate training and follow up (p = 1) (Table 10 & Figure 18).

Table 9. Mean ± SD ankle eversion strength (N) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) ankle eversion	4.98± 1.47	4.90± .836	10.92± 3.15	11.32± 2.33	35.82	1.11, 4.46	.003*
(MA) ankle eversion	3.88± 1.10	4.20± .900	9.52± 2.70	9.50± 2.71	20.31	1.10, 4.41	.008*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 10. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
(LA) ankle eversion	1	.039*	.006*	.046*	.009*	1
(MA) ankle eversion	1	.044*	.040*	.085	.086	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Strength: Ankle Invertors. By 1 month follow up, the mean score of less-affected ankle invertors increased from 6.92 N± 1.55 N to 12.40 N± 3.31 N, a 83% improvement (Table 11 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.09, 4.36) = 19.48, p = .009). Post hoc tests using the Bonferroni correction revealed no statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = .058), initial and follow up (p=.060), baseline and immediate training (p = .074), baseline and follow up (p = .079), and immediate training and follow up (p = 1) (Table 12 & Figure 18). The mean score of more-affected ankle invertors increased from 5.34 N± 1.10 N to 11.26 N± 2.88 N at 1 month follow up, a 115% improvement (Table 11 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.05, 4.23) = 24.43, p = .007). Post hoc tests using the Bonferroni correction revealed statistically significant differences on mean score between initial and immediate training (p = .048), initial and follow up (p=.028) and baseline and follow up (p = .041). No statistically difference were found between initial and baseline (p = .996), baseline and immediate training (p = .068) and immediate training and follow up (p = 1) (Table 12 & Figure 18).

Table 11. Mean ± SD ankle inversion strength (N) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) ankle inversion	6.60± 1.46	6.92± 1.55	12.78± 3.67	12.40± 3.31	19.48	1.09, 4.36	.009*
(MA) ankle inversion	5.06± 1.25	5.34± 1.10	11.26± 3.30	11.26± 2.88	24.43	1.05, 4.23	.007*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 12. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
(LA) ankle inversion	1	.058	.060	.074	.079	1
(MA) ankle inversion	.996	.048*	.028*	.068	.041*	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Strength: Ankle Plantarflexors. The mean score of less-affected ankle plantarflexors statistically increased from 7.96 N± 2.52 N to 15.92 N± 3.59 N at 1 month follow up, a 106% improvement (Table 13 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.08, 4.32) = 60.28$, $p = .001$). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training ($p = .025$), initial and follow up ($p=.002$), baseline and immediate training ($p = .014$), baseline and follow up ($p <.001$). No statistically differences were found between initial and baseline ($p = .634$) and immediate training and follow up ($p = 1$) (Table 14 & Figure 18). At 1 month follow up, the mean score of more-affected ankle plantarflexors statistically increased from 6.30 N± 2.47 N to 14.06 N± 3.11 N, a 138% improvement (Table 13 & Figure 17). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.06, 4.25) = 29.96$, $p = .004$). Post hoc tests revealed statistically significant differences on mean score between initial and follow up ($p=.002$) and baseline and follow up ($p < .001$). No statistically significant differences were found between initial and baseline ($p = 1$), initial and immediate training ($p = .123$), baseline and immediate training ($p = .081$) and immediate training and follow up ($p = 1$) (Table 14 & Figure 18).

Table 13. Mean ± SD ankle plantarflexion strength (N) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) ankle PF	7.36± 2.06	7.96± 2.52	15.12± 4.58	15.92± 3.59	60.28	1.08, 4.32	.001*
(MA) ankle PF	5.80± 2.07	6.30± 2.47	12.26± 5.36	14.06± 3.11	29.96	1.06, 4.25	.004*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 14. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
(LA) ankle PF	.634	.025*	.002*	.014*	<.001*	1
(MA) ankle PF	1	.123	.002*	.081	<.001*	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

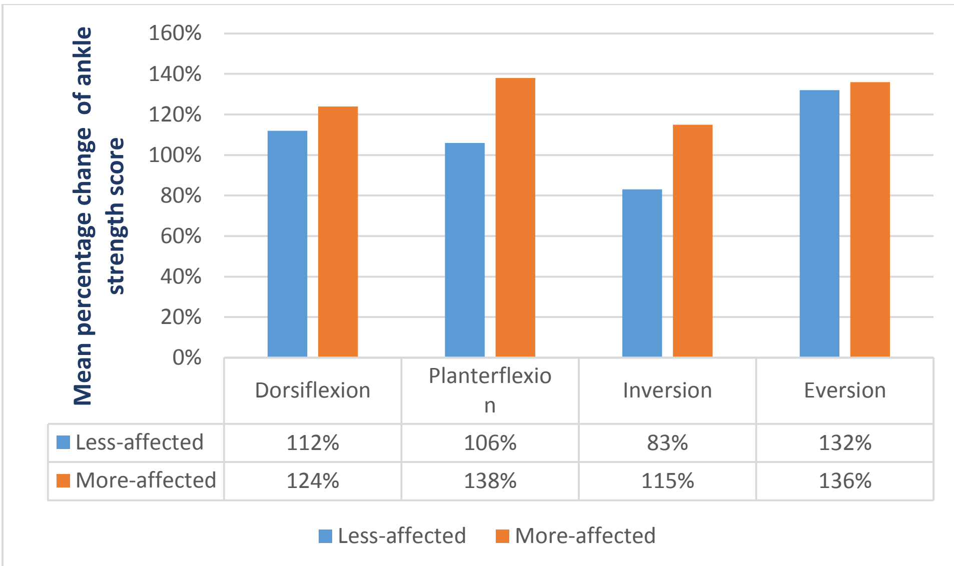


Figure 17. Ankle strength improvement chart

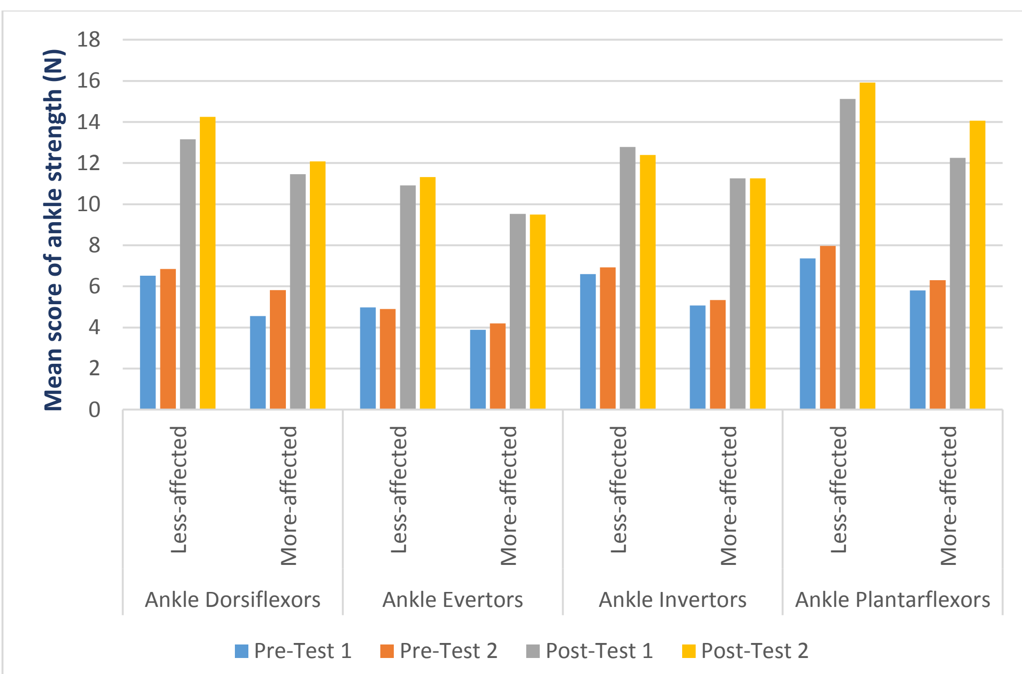


Figure 18. Change of ankle muscle strength prior to and after training

Strength: Knee Extensors. In addition to ankle strength changes, changes in the joints above were also found. At 1 month follow up, the mean score of the less-affected knee extensor increased from 13.94 N± 4.49 N to 16.88 N± 8.75 N, a 17% improvement, but it showed more improvement at 1 week post-training, improving to 17.02± 4.55 N (Table 15 & Figure 19). A repeated measures ANOVA did not show any statistically significant difference between different time points ($F(1.12, 4.50) = 2.44$, $p = .187$). Post hoc tests showed statistically significant differences on mean score between baseline and immediate training ($p = .024$). No statistically significant changes were seen between initial and baseline ($p = .823$), initial and immediate training ($p = .068$), initial and follow up ($p=1$), baseline and follow up ($p = 1$) and immediate training and follow up ($p = 1$) (Table 16 & Figure 20). The mean score of the more-affected knee extensor increased from 12.04 N± 4.06 N to 14.20 N± 6.95 N at 1 month follow up, a 17% improvement, but it showed more improvement at 1 week post-training, improving to 15.78 N± 5.17 N (Table 15 & Figure 19). A repeated measures ANOVA showed no statistically significant difference between different time points ($F(1.15, 4.62) = 3.97$, $p = .106$). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training ($p = .017$) and baseline and immediate training ($p = .035$). No statistically significant differences were found between initial and baseline ($p = .344$), initial and follow up ($p=1$), baseline and follow up ($p = 1$) and immediate training and follow up ($p = 1$) (Table 16 & Figure 20).

Strength: Knee Flexors. The mean score of less-affected knee flexor statistically increased from 11.24 N± 5.53 N to 14.52 N± 3.29 N at 1 month follow up, a 64% improvement (Table 15 & Figure 19). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.63, 6.52) = 7.87, p = .021). Post hoc tests revealed statistically significant differences on mean score between initial and follow up (p=.011); however, no statistically significant differences were found between initial and baseline (p = 1), initial and immediate training (p = .101), baseline and immediate training (p = .563), baseline and follow up (p = .370), and immediate training and follow up (p = 1) (Table 16 & Figure 20). The mean score of more-affected knee flexor increased at 1 month follow up from 10.04 N± 5.18 N to 14.42 N± 3.73 N, a 78% improvement (Table 15 & Figure 19). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.18, 4.72) = 11.68, p = .019). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training (p = .020) and initial and follow up (p=.017). No statistically significant differences were shown between initial and baseline (p = 1), baseline and immediate training (p = .248), baseline and follow up (p = .218), and immediate training and follow up (p = .238) (Table 16 & Figure 20).

Table 15. Mean ± SD knee strength (N) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) knee extension	12.92± 4.22	13.94± 4.49	17.02± 4.55	16.88± 8.75	2.44	1.12, 4.50	.187
(MA) knee extension	10.40± 3.84	12.04± 4.06	15.78± 5.17	14.20± 6.95	3.97	1.15, 4.62	.106
(LA) knee flexion	10.78± 3.82	11.24± 5.53	14.28± 4.55	14.52± 3.29	7.87	1.63, 6.52	.021*
(MA) knee flexion	10.40± 4.30	10.04± 5.18	13.48± 3.74	14.42± 3.73	11.68	1.18, 4.72	.019*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 16. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
(LA) knee extension	.823	.068	1	.024*	1	1
(MA) knee extension	.344	.017*	1	.035*	1	1
(LA) knee flexion	1	.101	.011*	.563	.370	1
(MA) knee flexion	1	.020*	.017*	.248	.218	.238

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

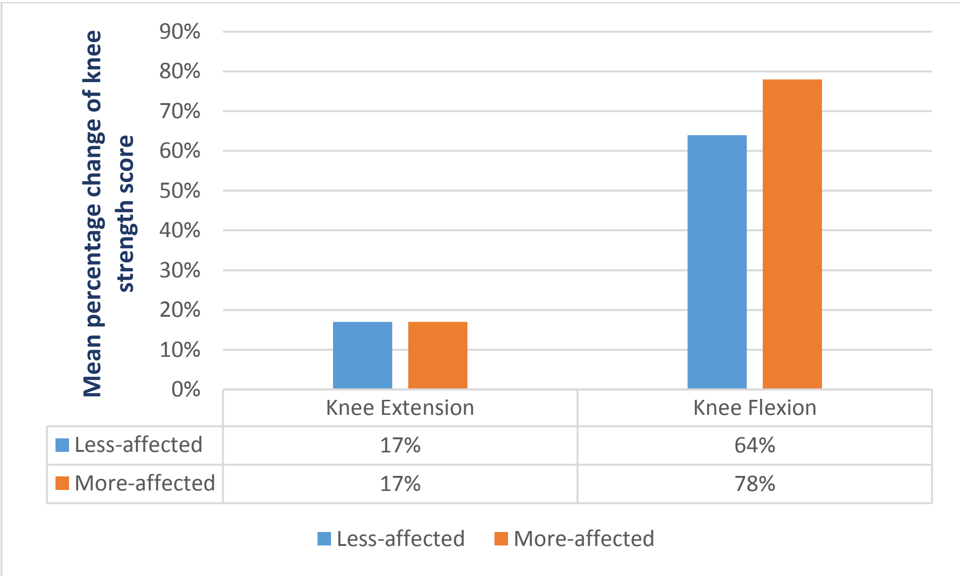


Figure 19. Knee strength improvement chart

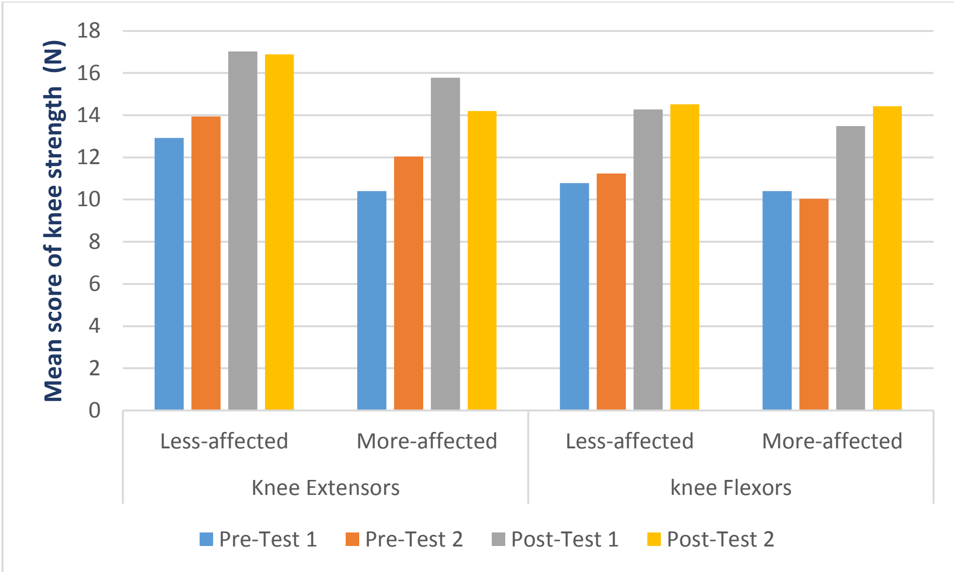


Figure 20. Change of knee muscle strength prior to and after training

Strength: Hip Abductors. The results showed that mean score of less-affected hip abductor at 1 month follow up increased from 10.18 N± 2.99 N to 13.84 N± 5.83 N, improving by 40% (Table 17 & Figure 21). A repeated measures ANOVA did not show a statistically significant difference between different time points ($F(1.11, 4.45) = 3.33$, $p = .134$). Post hoc tests revealed no statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .494$), initial and follow up ($p=.506$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 18 & Figure 22). The mean score of more-affected hip abductor increased from 10.02 N± 2.45 N to 12.64 N± 4.17 N at 1 month follow up, a 24% improvement (Table 17 & Figure 21). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.50, 5.99) = 12.99$, $p = .008$). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .092$), initial and follow up ($p=.050$), baseline and immediate training ($p =$

.170), baseline and follow up (p = .175), and immediate training and follow up (p = .464) (Table 18 & Figure 22).

Table 17. Mean ± SD hip abduction strength (N) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) hip AB	9.56± 2.69	10.18± 2.99	14.74± 6.18	13.84± 5.83	3.33	1.11, 4.45	.134
(MA) hip AB	9.12± 3.49	10.02± 2.45	14.18± 4.86	12.64± 4.17	12.99	1.50, 5.99	.008*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 18. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
(LA) hip AB	1	.494	.506	1	1	1
(MA) hip AB	1	.092	.050	.170	.175	.464

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Strength: Hip Adductors. The mean score of less-affected hip adductor statistically increased from 12.42 N± 5.63 N to 20.30 N± 8.87 N at 1 month follow up, a 64% improvement (Table 19 & Figure 21). A repeated measures ANOVA showed a statistically significant difference between different time points (F(2.05, 8.22) = 10.95, p = .005). Post hoc tests did not showed any statistically significant improvement on mean score between initial and baseline (p = 1), initial and immediate training (p = .178), initial and follow up (p=.095), baseline and immediate training (p = .161), baseline and follow up (p = .091), and immediate training and follow up (p = 1) (Table 20 & Figure 22). The mean score of more-affected hip adductor increased from 10.88 N± 5.77 N to 16.12 N± 8.53 N at 1 month follow up, a 51% improvement (Table 19 & Figure 21). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.40, 5.60) = 8.26, p = .026). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = .279), initial and follow up (p=.241), baseline and immediate training (p = .207), baseline and follow up (p = .234), and immediate training and follow up (p = 1) (Table 20 & Figure 22).

Table 19. Mean ± SD hip adduction strength (N) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) hip ADD	12.56± 6.96	12.42± 5.63	19.50± 9.66	20.30± 8.87	10.95	2.05, 8.22	.005*
(MA) hip ADD	11.18± 5.88	10.88± 5.77	16.34± 8.21	16.12± 8.53	8.26	1.40, 5.60	.026*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 20. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
(LA) hip ADD	1	.178	.095	.161	.091	1
(MA) hip ADD	1	.279	.241	.207	.234	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Strength: Hip Extensors. The mean score of less-affected hip extensor improved 29% at 1 month follow up, increasing from 10.16 N± 3.22 N to 13.12 N± 5.04 N (Table 21 & Figure 21). A repeated measures ANOVA revealed no statistically significant difference between different time points (F(1.61, 6.45) = 3.81, p = .086). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = .063), initial and follow up (p=.308), baseline and immediate training (p = .727), baseline and follow up (p = .422), and immediate training and follow up (p = 1) (Table 22 & Figure 22). The mean score of more-affected hip extensor increased from 9.10 N± 3.59 N to 11.06 N± 3.99 N at 1 month follow up, a 26% improvement (Table 21 & Figure 21). A repeated measures ANOVA showed a statistically significant difference between different time points (F(2.01, 8.06) = 8.63, p = .010). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = .171), initial and follow up (p=.518), baseline and immediate training (p = .126), baseline and follow up (p = .269), and immediate training and follow up (p = .104) (Table 22 & Figure 22).

Table 21. Mean ± SD hip extension strength (N) prior changes to and after training

	Initial baseline	Baseline	Immediate training	Follow up	F	df	p-value
(LA) hip Ex	10.70± 5.29	10.16± 3.22	13.46± 5.62	13.12± 5.04	3.81	1.61, 6.45	.086
(MA) hip Ex	9.76± 3.77	9.10± 3.59	12.74± 4.74	11.06± 3.99	8.63	2.01, 8.06	.010*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 22. Post hoc test showed the difference between time points

p-value	Initial and baseline	Initial and immediate training	Initial and follow up	Baseline and immediate training	Baseline and follow up	Immediate training and follow up
(LA) hip Ex	1	.063	.308	.727	.422	1
(MA) hip Ex	1	.171	.518	.126	.269	.104

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Strength: Hip Flexors. The mean score of less-affected hip flexor increased from 11.78 N± 3.28 N to 14.50 N± 2.78 N at 1 month post-training, a 26% improvement (Table 23 & Figure 21). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.39, 5.57) = 10.25, p = .017). Post hoc tests revealed statistically significant differences on mean score between initial and follow up (p=.034), but no statistical differences between initial and baseline (p = 1), initial and immediate training (p = .320), baseline and immediate training (p = .096), baseline and follow up (p = .071), and immediate training and follow up (p = 1) (Table 24 & Figure 22). The mean score of more-affected hip flexor increased from 10.22 N± 2.87 N to 12.72 N± 2.77 N at 1 month post-training, a 27% improvement (Table 23 & Figure 21). A repeated measures ANOVA showed a statistically significant difference between different time points (F(2.01, 8.04) = 13.15, p = .003). Post hoc tests showed statistically significant differences on mean score between initial and follow up (p=.023). However, there were no statistical differences between initial and baseline (p = 1), initial and immediate training (p = .070), baseline and immediate training (p = .109), baseline and follow up (p = .073), and immediate training and follow up (p = 1) (Table 24 & Figure 22).

Table 23. Mean ± SD hip flexion strength (N) changes prior to and after training

	Initial baseline	Baseline	Immediate training	Follow up	F	df	p-value
(LA) hip Fx	10.30± 1.60	11.78± 3.28	13.86± 3.86	14.50± 2.78	10.25	1.39, 5.57	.017*
(MA) hip Fx	9.34± 2.39	10.22± 2.87	14.44± 4.79	12.72± 2.77	13.15	2.01, 8.04	.003*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 24. Post hoc test showed the difference between time points

p-value	Initial and baseline	Initial and immediate training	Initial and follow up	Baseline and immediate training	Baseline and follow up	Immediate training and follow up
(LA) hip Fx	1	.320	.034*	.096	.071	1
(MA) hip Fx	1	.070	.023*	.109	.073	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

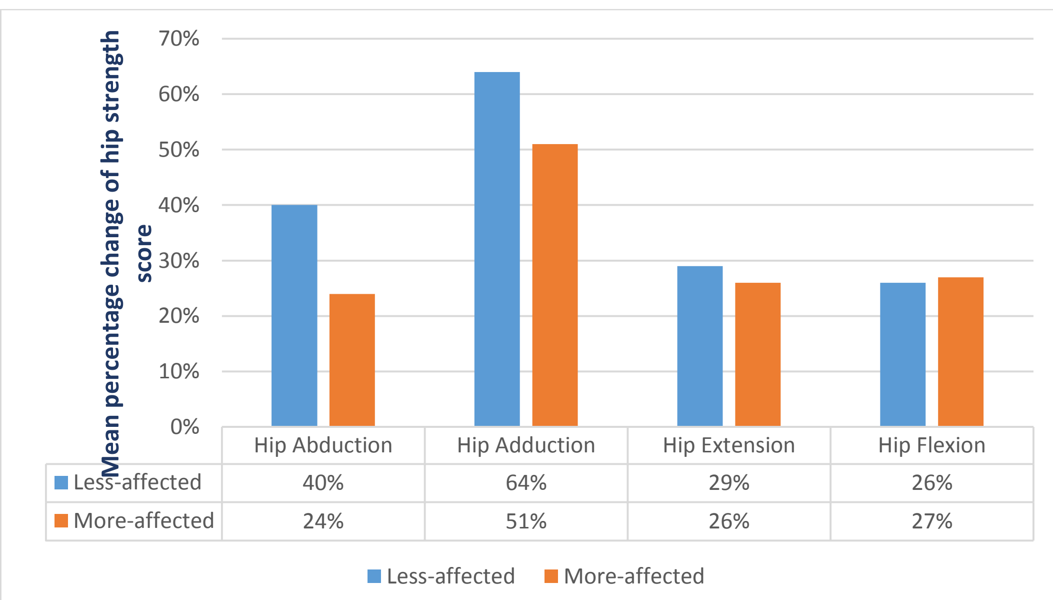


Figure 21. Hip strength improvement chart

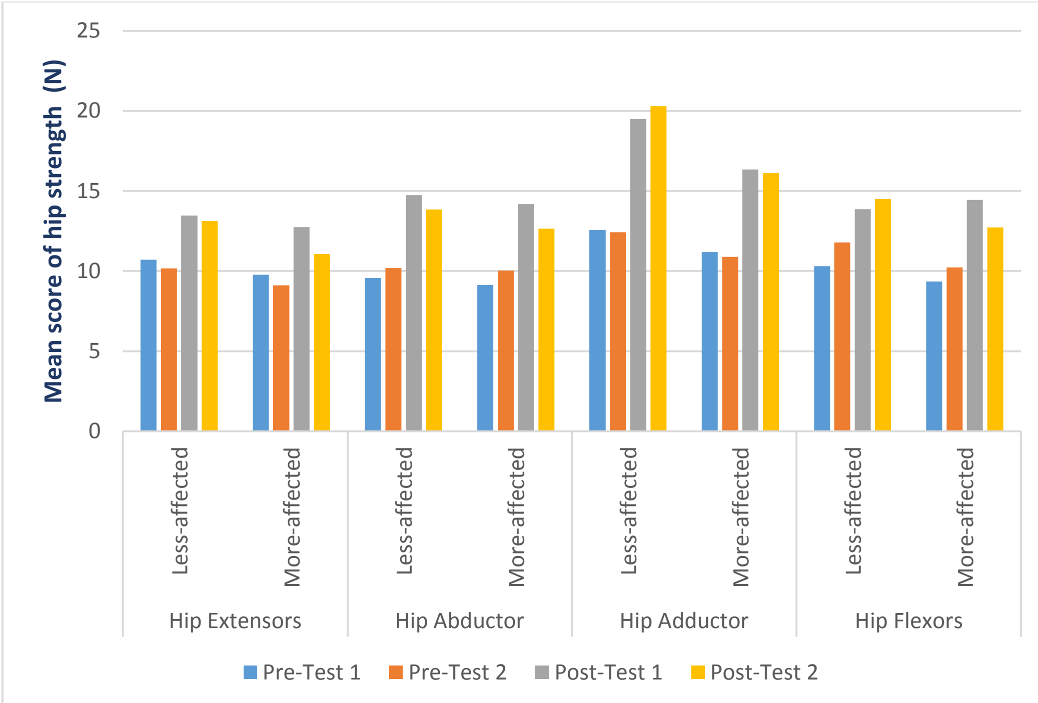


Figure 22. Change of hip muscle strength prior to and after training

Muscle Tone

Muscle tone: Gastrocnemius. Data from the Tardieu Scale of Spasticity were analyzed for all four time points. The results revealed that the mean R2–R1 value of the less-affected gastrocnemius significantly decreased from 18.40°± 7.70° to 9°± 5.52° at 1 week post-training, and then decreased to 7.20°± 4.32° at 1 month follow up, a 60% decrease, which indicates improvement in tone (Table 25 & Figure 23). A repeated measures ANOVA did not show a statistically significant difference between different time points (F(1.12, 4.48) = 6.48, p = .055). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = .466), initial and follow up (p=.332), baseline and immediate training (p = .263), baseline and follow up (p = .099), and immediate training and follow up (p = .320) (Table 26 & Figure 24).

There was a reduction of the R2–R1 value of the more-affected gastrocnemius 1 month after training, from 19.80°± 8.98° to 4.60°± .548°, an 72% decrease (Table 25 & Figure 23). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.18, 4.72) = 7.32$, $p = .043$). Post hoc tests revealed no statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .508$), initial and follow up ($p=.213$), baseline and immediate training ($p = .514$), baseline and follow up ($p = .121$), and immediate training and follow up ($p = .244$) (Table 26 & Figure 24).

Muscle Tone: Hamstrings. There was a reduction of the R2–R1 value of the less-affected hamstring 1 month after training, from 22.80°± 9.33° to 12.20°± 2.49°, a 42% decrease (Table 25 & Figure 23). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.88, 7.53) = 11.72$, $p = .005$). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .127$), initial and follow up ($p=.065$), baseline and immediate training ($p = .127$), baseline and follow up ($p = .175$), and immediate training and follow up ($p = .274$) (Table 26 & Figure 24).

There was a reduction of the R2–R1 value of the more-affected hamstring 1 month after training from 29.60°± 15.40° to 10.80°± 2.38°, a 55% decrease (Table 25 & Figure 23). A repeated measures ANOVA showed no statistically significant difference between different time points ($F(1.06, 4.25) = 6.57$, $p = .058$). Post hoc tests revealed no statistically significant differences on mean score between initial and baseline ($p = .244$), initial and immediate training ($p = .366$), initial and follow up ($p=.226$), baseline and immediate training (p = .749), baseline and follow up (p = .406), and immediate training and follow up (p = .154) (Table 26 & Figure 24).

Table 25. Mean ± SD Tardieu Scale of Spasticity (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) gastrocnemius (R2–R1)	25.40± 17.55	18.40± 7.70	9± 5.52	7.20± 4.32	6.48	1.12, 4.487	.055
(MA) gastrocnemius (R2–R1)	24.80± 14.22	19.80± 8.98	8.60± 2.70	4.60± .548	7.32	1.18, 4.72	.043*
(LA) hamstring (R2–R1)	29± 9.67	22.80± 9.33	16.60± 5.59	12.20± 2.49	11.72	1.88, 7.53	.005*
(MA) hamstring (R2–R1)	33.60± 15.04	29.60± 15.40	15.40± 1.81	10.80± 2.38	6.57	1.06, 4.25	.058

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 26. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
p-value ((LA) gastrocnemius)	1	.466	.332	.263	.099	.320
p-value ((MA) gastrocnemius)	1	.508	.213	.514	.121	.244
p-value ((LA) hamstring)	1	.127	.065	.127	.175	.274
p-value ((MA) hamstring)	.244	.366	.226	.749	.406	.154

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

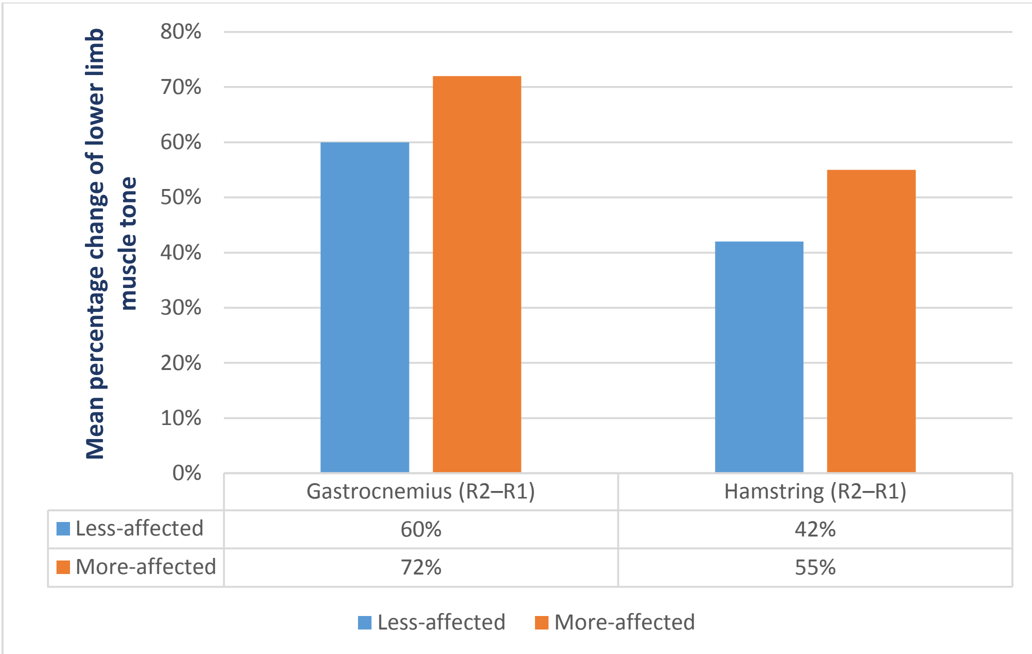


Figure 23. Muscle tone improvement chart

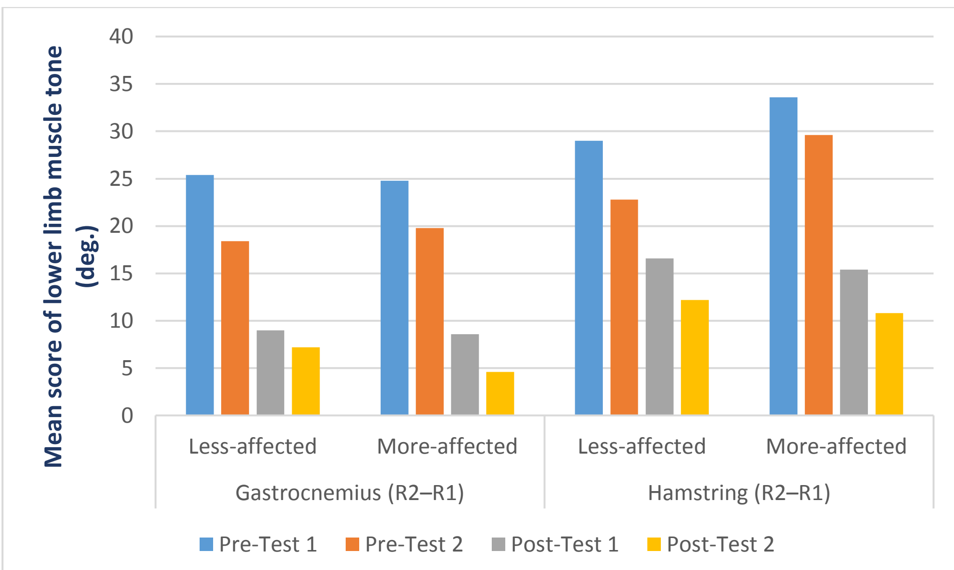


Figure 24. Change of Tardieu Scale of Spasticity score prior to and after training

Muscle Architecture

Muscle Architecture: Bilateral Achilles Tendon CSA. Data from the ultrasound were analyzed for two time points. Comparison between the baseline testing (2nd pre-test) and 1 month follow up showed a non-significant decrease in bilateral (less/more-affected) Achilles tendon CSA from 37.50 mm^2 ± 9 mm^2 to 34.52 mm^2± 6.80 mm^2, a 6% decline and from 36.30 mm^2± 10.70 mm^2 to 36.50 mm^2± 9.04 mm^2, a 2% decline, respectively (Table 27 & Figure 25). A repeated measures ANOVA failed to reveal any statistically significant difference between the two time points for bilateral (less/more-affected) Achilles tendon CSA (F(1, 4) = 1.58, p = .277), (F(1, 4) = .024, p = .884), respectively (Figure 26). At 1 month follow up, the CSA of the more affected Achilles tendon was 6% larger than the less affected Achilles tendon.

Muscle Architecture: Bilateral Medial Gastrocnemius CSA. Comparison between the baseline testing and 1 month follow up showed a non-significant increase in bilateral (less/more-affected) medial gastrocnemius CSA from 2.57 cm^2± 1.01 cm^2 to 2.85 cm^2± 1.08 cm^2 (12% improvement) and 2.30 cm^2± .551 cm^2 to 2.59 cm^2± .650 cm^2 (13% improvement), respectively (Table 27 & Figure 25). When comparing the baseline testing and 1 month follow up measurements within the groups (ANOVA), there was no statistically significant difference between the two time points of bilateral (less/more-affected) medial gastrocnemius CSA (F(1, 4) = 1.76, p = .255), (F(1, 4) = 3.73, p = .125), respectively (Figure 26). At 1 month follow up, the medial gastrocnemius muscles on the more affected sides had smaller CSA values than those on the less affected sides by 9%.

Muscle Architecture: Bilateral Tibialis Anterior CSA. Comparison between the baseline testing and 1 month follow up showed significant increase in less-affected tibialis anterior CSA, which improved 11%, from 2.57 cm^2±.81 cm^2 to 2.89 cm^2± 1.04 cm^2 (Table 27 & Figure 25). A repeated measures ANOVA showed a statistically significant difference between the two time points (F(1, 4) = 8.70, p = .042) (Figure 26). On the other hand, the comparison between the two tests (baseline testing and follow up) of the more-affected tibialis anterior CSA showed non-significant improvement from

2.76 cm^2±.703 cm^2 to 3.07 cm^2± 1.05 cm^2, a 9% improvement (Table 27 & Figure 25). A repeated measures ANOVA showed that there was no statistically significant difference between the two time points ($F(1, 4) = 3.47$, $p = .136$) (Figure 26). At 1 month follow up, the CSA of the more affected tibialis anterior was 6% larger than the less affected one.

Table 27. Mean ± SD CSA of AT, TA and gastrocnemius changes prior to and after training

	Baseline	**Follow up**	**F**	**df**	**p-value**
(LA) Achilles tendon CSA (mm^2)	37.50 ± 9	34.52± 6.80	1.58	1,4	.277
(MA) Achilles tendon CSA (mm^2)	36.30± 10.70	36.50± 9.04	.024	1,4	.884
(LA) medial gastrocnemius CSA (cm^2)	2.57± 1.01	2.85± 1.08	1.76	1,4	.255
(MA) medial gastrocnemius CSA (cm^2)	2.30± .551	2.59± .650	3.73	1,4	.125
(LA) tibialis anterior CSA (cm^2)	2.57±.81	2.89± 1.04	8.70	1,4	.042*
(MA) tibialis anterior CSA (cm^2)	2.76±.703	3.07± 1.05	3.47	1,4	.136

*. Significant difference pre to post ($p<.05$).
Note. (LA)= less-affected & (MA)= more-affected.

Muscle Architecture: Bilateral Tibialis Anterior Pennation Angle. The results showed that bilateral (less/more-affected) tibialis anterior pennation angle increased at 1 month follow up, from 15.09°± 4.26° to 15.60°± 4.80°, 13.03°±1.63° to 13.24°±2.26°, a 3% and 2% improvement, respectively (Table 28 & Figure 25). A repeated measures ANOVA failed to reveal any statistically significant difference between different time point of the bilateral (less/more-affected) tibialis anterior pennation angle ($F(1, 4) = .338$, $p = .592$), and ($F(1, 4) = .059$, $p = .820$) (Figure 26). At 1 month follow up, the tibialis anterior pennation angle on the more affected sides was 15% smaller than those on the less affected sides.

Table 28. Mean ± SD TA pennate angle (deg.) changes prior to and after training

	Baseline	**Follow up**	**F**	**df**	**p-value**
(LA) Tibialis anterior pennate angle	15.09± 4.26	15.60± 4.80	.338	1,4	.592
(MA) Tibialis anterior pennate angle	13.03±1.63	13.24±2.26	.059	1,4	.820

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Muscle Architecture: Bilateral Tibialis Anterior Thickness. Average bilateral (less/more-affected) tibialis anterior thickness increased at 1 month follow up, from 22.77 mm ± 3.87 mm to 24.61 mm ± 3.79 mm (9% improvement) and from 23.47 mm ±4.37 mm to 24.53 mm ±3.13 mm (6% improvement), respectively (Table 29 & Figure 25). A repeated measures ANOVA failed to reveal any statistically significant difference between different time points of the bilateral (less/more-affected) tibialis anterior thickness ($F(1, 4) = 2.95$, $p = .161$), ($F(1, 4) = 1.14$, $p = .344$) (Figure 26). The tibialis anterior thickness on the more affected sides had higher values than those on the less affected sides by 0.32%.

Table 29. Mean ± SD TA thickness (mm) changes prior to and after training

	Baseline	**Follow up**	**F**	**df**	**p-value**
(LA) tibialis anterior thickness	22.77± 3.87	24.61± 3.79	2.95	1,4	.161
(MA) tibialis anterior thickness	23.47±4.37	24.53±3.13	1.14	1,4	.344

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

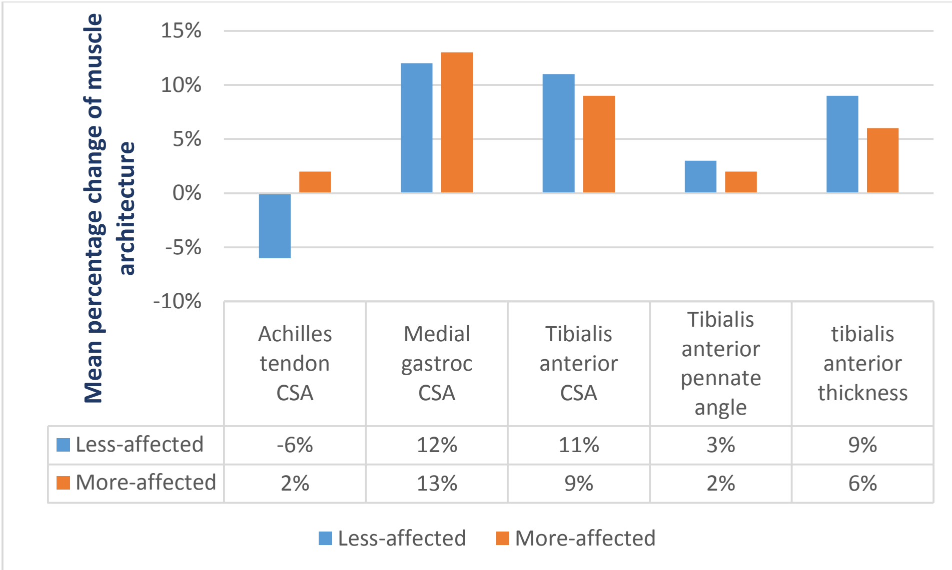


Figure 25. Ankle muscle architecture change chart

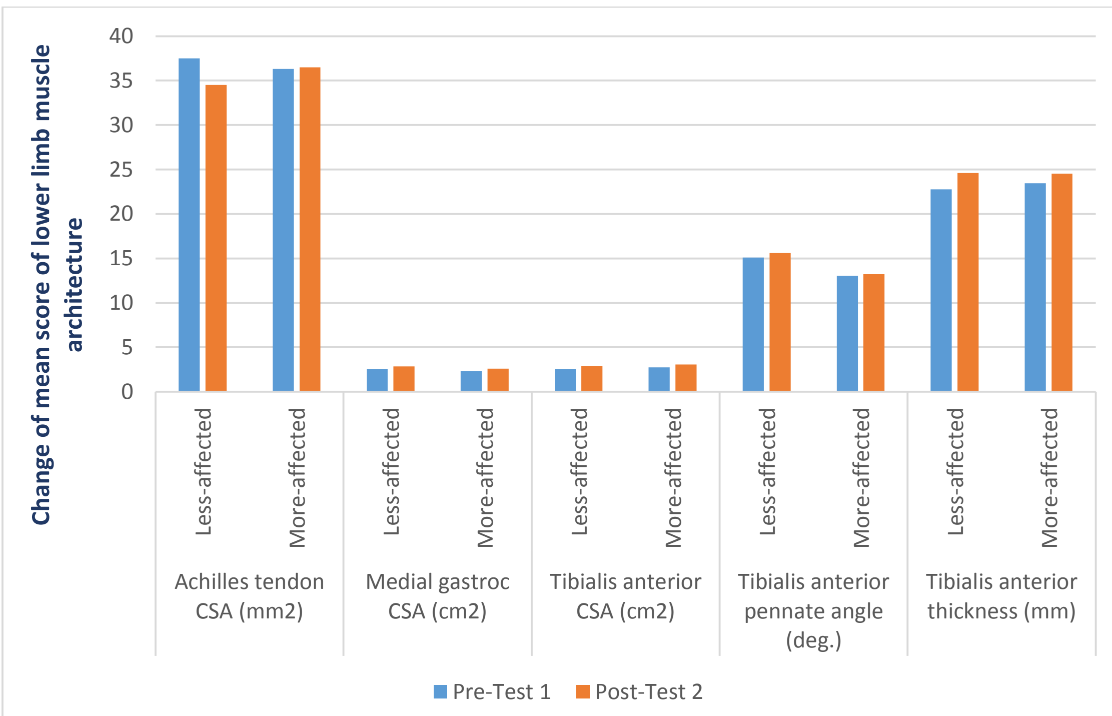


Figure 26. Change of ankle muscle architecture mean score prior to and after training

ROM

ROM: Ankle Dorsiflexion. Data from the goniometer were analyzed at all four time points. The results show that the mean active ROM of the less-affected ankle dorsiflexors increased from -1.40°± 11.90° to 7.40°± 11.14° at 1 month follow up, a 72%

improvement (Table 30 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.45, 5.81) = 16.17$, $p = .005$). Post hoc tests using the Bonferroni correction showed a statistical significant change between initial and follow up ($p=.034$). No statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .094$), baseline and immediate training ($p = .111$), baseline and follow up ($p = .062$), and immediate training and follow up ($p = 1$) (Table 31 & Figure 28). The results also show that, by 1 month follow up, the mean active ROM of the more-affected ankle dorsiflexors significantly increased from -26.60°± 10.43° to -13.20°± 7.72°, a 54% improvement (Table 30 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.32, 5.30) = 14.40$, $p = .009$). Post hoc tests revealed statistically significant differences on mean score between time points initial and follow up ($p = .008$) and baseline and immediate training ($p = .012$). No statistically significant changes emerged between initial and baseline ($p = 1$), initial and immediate training ($p = .131$), baseline and immediate training ($p = .071$) and immediate training and follow up ($p = 1$) (Table 31 & Figure 29).

By 1 month follow up, the mean score of passive ROM of the less-affected ankle dorsiflexors increased from 8.8°± 8.81° to 14.4°± 9.81°, a 55% improvement (Table 30 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between time points ($F(2.03, 8.12) = 10.69$, $p = .005$). Post hoc tests using the Bonferroni correction did not show any statistical significant change between initial and baseline ($p = 1$), initial and immediate training ($p = .170$), initial and follow up ($p=.068$), baseline and immediate training ($p = .083$), baseline and follow up ($p = .197$), and immediate training and follow up (p = 1) (Table 31 & Figure 28). For the same time point, the mean score of passive ROM of the more-affected ankle dorsiflexors statistically increased from -10.40°± 11.97° to 2.60°± 11.95°, a 295% improvement (Table 30 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.97, 7.88) = 30.95$, $p < .001$). Post hoc tests using the Bonferroni correction revealed statistically significant differences on mean score between the following time points: initial and immediate training ($p = .013$), initial and follow up ($p=.022$), baseline and immediate training ($p = .040$), baseline and follow up ($p = .004$). No statistically significant changes were seen between initial and baseline ($p = 1$) and immediate training and follow up ($p = .976$). (Table 31 & Figure 29).

Table 30. Mean ± SD ankle dorsiflexion (DF) ROM (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
Active (LA) DF	.00± 10	-1.40± 11.90	7.80± 12.39	7.40± 11.14	16.17	1.45, 5.81	.005*
Active (MA) DF	-27± 7.31	-26.60± 10.43	-18± 10.65	-13.20± 7.72	14.40	1.32, 5.30	.009*
Passive (LA) DF	7.60± 9.34	8.8± 8.81	14.2± 10.15	14.4± 9.81	10.69	2.03, 8.12	.005*
Passive (MA) DF	-10± 12.43	-10.40± 11.97	-.80± 10.80	2.60± 11.95	30.952	1.97, 7.88	<.001*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 31. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
Active (LA) DF	1	.094	.034*	.111	.062	1
Active (MA) DF	1	.131	.008*	.012*	.071	1
Passive (LA) DF	1	.170	.068	.083	.197	1
Passive (MA) DF	1	.013*	.022*	.040*	.004*	.976

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

ROM: Ankle Plantarflexion. The mean score of active ROM of the less-affected ankle plantarflexors increased from 49.80°± 8.25° to 61.20°± 4.14° at 1 month follow up, a 25% improvement (Table 32 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.79, 7.19) = 13.10$, $p = .004$). Post hoc tests using the Bonferroni correction showed no statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .135$), initial and follow up ($p=.111$), baseline and immediate training ($p = .060$), baseline and follow up ($p = .060$), and immediate training and follow up ($p = 1$) (Table 33 & Figure 28). By 1 month follow up, the mean score of active ROM of the more-affected ankle plantarflexors increased from 47.80°± 8.19° to 56°± 6.04° (19% improvement) (Table 32 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(2.27, 9.08) = 29.30$, $p < .001$). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training ($p = .005$), initial and follow up ($p=.005$) and baseline and immediate training ($p = .043$). No statistically significant changes were seen between initial and baseline ($p = .613$), baseline and follow up ($p = .118$), and immediate training and follow up ($p = .635$) (Table 33 & Figure 29).

By 1 month follow up, the mean score of passive ROM of the less-affected ankle plantarflexors showed a 16% improvement, increasing from 60°± 8.38° to 69.60°± 7.95° (Table 32 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different timepoints ($F(1.56, 6.24) = 11.42$, $p = .010$). Post hoc tests showed no statistically significant differences on mean score between initial and baseline ($p = .538$), initial and immediate training ($p = .234$), initial and follow up ($p=.088$), baseline and immediate training (p = .199), baseline and follow up (p = .098), and immediate training and follow up (p = 1) (Table 33 & Figure 28). The 1 month follow up mean score of passive ROM of the more-affected ankle plantarflexors increased from 58.20°± 7.46° to 66°± 7.90°, a 14% improvement (Table 32 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(2.01, 8.04) = 31.19$, $p < .001$). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training (p = .025), initial and follow up (p=.006), baseline and immediate training (p = .018), baseline and follow up (p = .015). No statistically significant changes were seen between initial and baseline (p = .148), and immediate training and follow up (p = 1). (Table 33 & Figure 29).

Table 32. Mean ± SD ankle plantarflexion (PF) ROM (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
Active (LA) PF	48.80± 7.79	49.80± 8.25	62± 3.67	61.20± 4.14	13.10	1.79, 7.19	.004*
Active (MA) PF	42.80± 7.59	47.80± 8.19	58.60± 3.97	56± 6.04	29.30	2.27, 9.08	<.001*
Passive (LA) PF	58± 10.65	60± 8.38	67.40± 4.33	69.60± 7.95	11.42	1.56, 6.24	.010*
Passive (MA) PF	54.20± 9.75	58.20± 7.46	63.80± 6.72	66± 7.90	31.19	2.01, 8.04	<.001*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 33. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
Active (LA) PF	1	.135	.111	.060	.060	1
Active (MA) PF	.613	.005*	.005*	.043*	.118	.635
Passive (LA) PF	.538	.234	.088	.199	.098	1
Passive (MA) PF	.148	.025*	.006*	.018*	.015*	1

*. The mean difference is significant at the .05 level.
Note. (LA)= less-affected & (MA)= more-affected.

ROM: Ankle Eversion. The mean score of active ROM of the less-affected ankle evertors increased from 13°± 4.69° to 20.80°± 7.19°, a 63% improvement, 1 month follow up (Table 34 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(2.37, 9.47) = 17.99$, $p <.001$). Post hoc tests revealed statistically significant differences on mean score between initial and follow up ($p=.016$) and baseline and follow up ($p = .036$). No statistically significant changes were seen between initial and baseline ($p = 1$), initial and immediate training ($p = .091$), baseline and immediate training ($p = .106$) and immediate training and follow up ($p = 1$) (Table 35 & Figure 28). At 1 month follow up, the mean score of active ROM of the more-affected ankle evertors increased from 9.40°± 2.88° to 19.20°± 6.41°, a 107% improvement (Table 34 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.04, 4.18) = 21.83$, $p = .008$). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training ($p = .020$), baseline and immediate training ($p = .014$). There were no statistically significant changes between initial and baseline ($p = .196$), initial and follow up ($p=.067$), baseline and follow up ($p = .065$), and immediate training and follow up ($p = .375$) (Table 35 & Figure 29).

By 1 month follow up, the mean score of passive ROM of the less-affected ankle evertors increased from 19.20°± 8.01° to 29.60°± 7.70°, an increase of 67% (Table 34 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.33, 5.32) = 8.82$, $p = .025$). Post hoc tests showed no statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .272$), initial and follow up ($p=.152$), baseline and immediate training (p = .346), baseline and follow up (p = .220), and immediate training and follow up (p = 1) (Table 35 & Figure 28). The mean score of passive ROM of the more-affected ankle evertors increased from 16.20°±3.96° to 28.20°±7.25°, improving 77% at 1 month follow up (Table 34 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.81, 7.27) = 11.97$, $p = .006$). Post hoc tests using the Bonferroni correction revealed that there were no statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = .232), initial and follow up (p=.084), baseline and immediate training (p = .157), baseline and follow up (p = .092), and immediate training and follow up (p = 1) (Table 35 & Figure 29).

Table 34. Mean ± SD ankle eversion ROM (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
Active (LA) eversion	13.80± 6.01	13± 4.69	19.20± 7.53	20.80± 7.19	17.99	2.37, 9.47	<.001*
Active (MA) eversion	8.20± 2.38	9.40± 2.88	15.80± 3.76	19.20± 6.41	21.83	1.04, 4.18	.008*
Passive (LA) eversion	18.40± 6.84	19.20± 8.01	27± 8.42	29.60± 7.70	8.82	1.33, 5.32	.025*
Passive (MA) eversion	15.20± 3.11	16.20±3.96	25± 8.39	28.20±7.25	11.97	1.81, 7.27	.006*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 35. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
Active (LA) eversion	1	.091	.016*	.106	.036*	1
Active (MA) eversion	.196	.020*	.067	.014*	.065	.375
Passive (LA) eversion	1	.272	.152	.346	.220	1
Passive (MA) eversion	1	.232	.084	.157	.092	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

ROM: Ankle Inversion. The mean score of active ROM of the less-affected ankle invertors increased from 20° ± 9.72° to 30.80° ± 8.10° at 1 month follow up, improving by 72% (Table 36 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.75, 7.00) = 15.68$, $p = .003$). Post hoc tests revealed a statistically significant differences on mean score between initial and immediate training ($p = .030$) and baseline and immediate training ($p = .018$). No statistically significant changes were seen between initial and baseline ($p = 1$), initial and follow up ($p=.099$), baseline and follow up ($p = .242$), and immediate training and follow up ($p = 1$) (Table 37 & Figure 28). The results show that, by 1 month follow up, the mean active ROM of the more-affected ankle invertors significantly increased from 18.80° ± 9.03° to 26.80° ± 7.39°, a 62% improvement (Table 36 & Figure 27). Between different time points, a repeated measures ANOVA showed a statistically significant difference ($F(1.84, 7.38) = 17.21$, $p = .002$). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training ($p = .018$) and baseline and immediate training ($p = .021$). No statistically significant changes were seen between initial and baseline ($p = .636$), initial and follow up ($p=.059$), baseline and follow up ($p = .249$), and immediate training and follow up ($p = 1$) (Table 37 & Figure 29).

The mean score of passive ROM of the less-affected ankle invertors improved 25%, increasing from 31.80° ± 7.01° to 39.40° ± 6.87° at 1 month follow up (Table 36 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.55, 6.21) = 15.73$, $p = .005$). Post hoc tests showed statistically significant differences on mean score between baseline and follow up ($p = .030$). No statistically significant changes were seen between initial and baseline ($p = 1$), initial and immediate training (p = .116), initial and follow up (p=.070), baseline and immediate training (p = .058) and immediate training and follow up (p = 1). (Table 37 & Figure 28). By 1 month follow up, the mean score of passive ROM of the more-affected ankle invertors significantly increased from 29.60° ± 4.15° to 39°± 4.35°, a 32% improvement (Table 36 & Figure 27). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(1.35, 5.41) = 47.07$, $p < .001$). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training (p = .030), initial and follow up (p=.003), baseline and immediate training (p = .014) and baseline and follow up (p = .001). No statistically significant changes were seen between initial and baseline (p = .515) and immediate training and follow up (p = 1) (Table 37 & Figure 29).

Table 36. Mean ± SD ankle inversion ROM (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
Active (LA) inversion	18.20 ± 6.64	20± 9.72	33± 10	30.80 ± 8.10	15.68	1.75, 7	.003*
Active (MA) inversion	14.80 ± 8.87	18.80 ± 9.03	26.80 ± 8.10	26.80 ± 7.39	17.21	1.84, 7.38	.002*
Passive (LA) inversion	30± 4.63	31.80 ± 7.01	39.40 ± 7.66	39.40 ± 6.87	15.73	1.55, 6.21	.005*
Passive (MA) inversion	27.40 ± 4.09	29.60 ± 4.15	38.20 ± 5.49	39± 4.35	47.07	1.35, 5.41	.001*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 37. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
Active (LA) inversion	1	.030*	.099	.018*	.242	1
Active (MA) inversion	.636	.018*	.059	.021*	.249	1
Passive (LA) inversion	1	.116	.070	.058	.030*	1
Passive (MA) inversion	.515	.030*	.003*	.014*	.001*	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

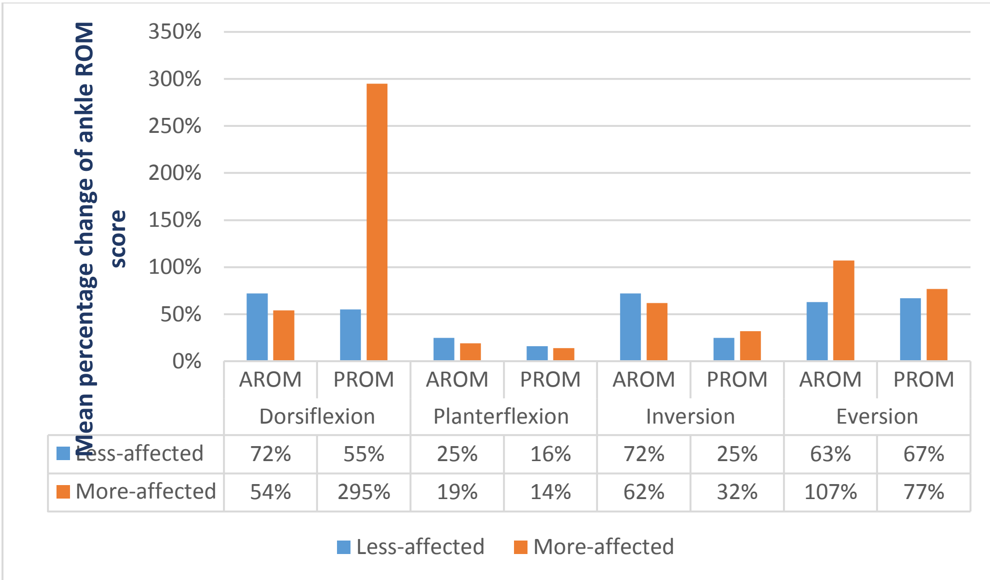


Figure 27. Ankle ROM improvement chart

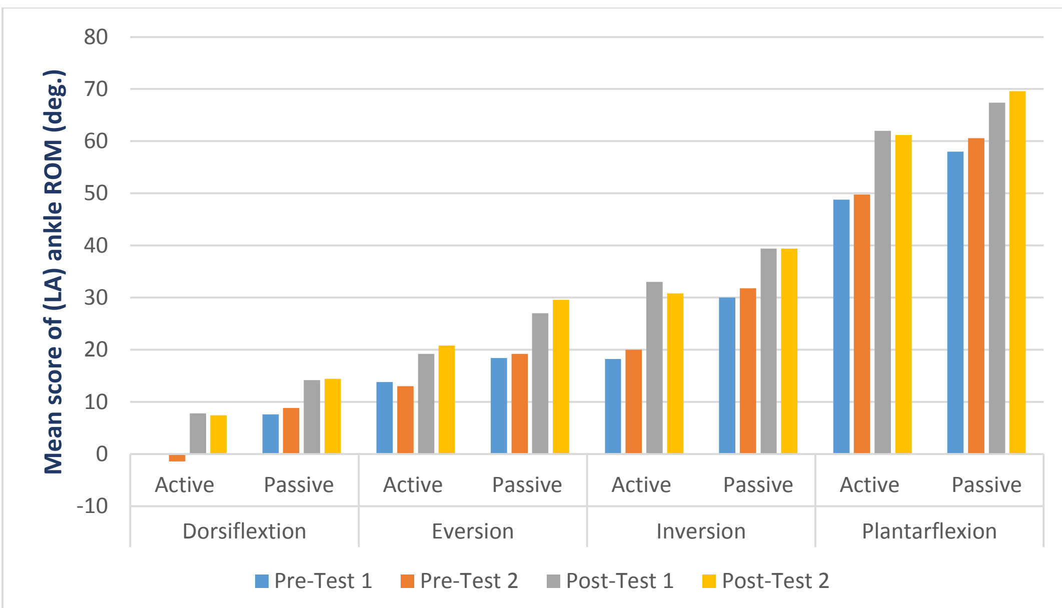


Figure 28. Change of (LA) ankle ROM mean score prior to and after training

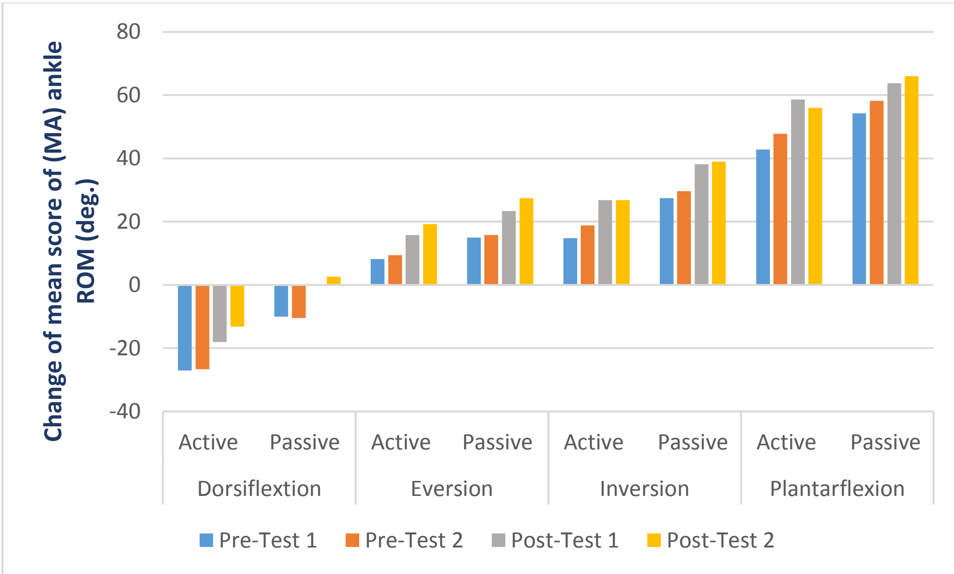


Figure 29. Change of (MA) ankle ROM mean score prior to and after training

ROM: Knee Extension. The mean score of active ROM of the less-affected knee extensor did not show any significant improvement, as shown by repeated measures ($F(1.44, 5.75) = .607$, $p = .525$) (Table 38 & Figure 30). Post hoc tests showed no statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 39 & Figure 31). Similarly, the mean score of active ROM of the more-affected knee extensor did not show any significant improvement, as shown by a repeated measures ANOVA ($F(1.10, 4.41) = 1.26$, $p = .326$) (Table 38 & Figure 30). Post hoc tests using the Bonferroni correction did not reveal any statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = 652$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 39 & Figure 31).

By 1 month follow up, the mean score of passive ROM of the less-affected knee extensor slightly increased from 1.40°± 3.91° to 1.60°± .548° (11% improvement).

However, the change was not significant (F(1.24, 4.97) = .014, p = .945) (Table 38 & Figure 30). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 39 & Figure 31). The mean score of passive ROM of the more-affected knee extensor improved from .80°± 3.42° to 1.60 °± 1.14° (25% improvement) at 1 month follow up (Table 38 & Figure 30). However, it was not significant (F(1.64, 6.58) = .516, p = .586). Post hoc tests revealed no statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 39 & Figure 31).

Table 38. Mean ± SD knee extension ROM (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
Active (LA) knee extension	-1± 3.46	-2± 4.47	-.80± 4.86	-.40± .89	.607	1.44, 5.75	.525
Active (MA) knee extension	-1.80± 4.60	-3± 6.70	-1.80 ± 5.76	-.20 ± 1.64	1.26	1.10, 4.41	.326
Passive (LA) knee extension	1.60± 2.96	1.40± 3.91	1.60± 1.81	1.60± .548	.014	1.24, 4.97	.945
Passive (MA) knee extension	.60 ± 3.20	.80± 3.42	1.0± 1.73	1.60 ± 1.14	.516	1.64, 6.58	.586

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 39. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
Active (LA) knee extension	1	1	1	1	1	1
Active (MA) knee extension	1	1	1	.652	1	1
Passive (LA) knee extension	1	1	1	1	1	1
Passive (MA) knee extension	1	1	1	1	1	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

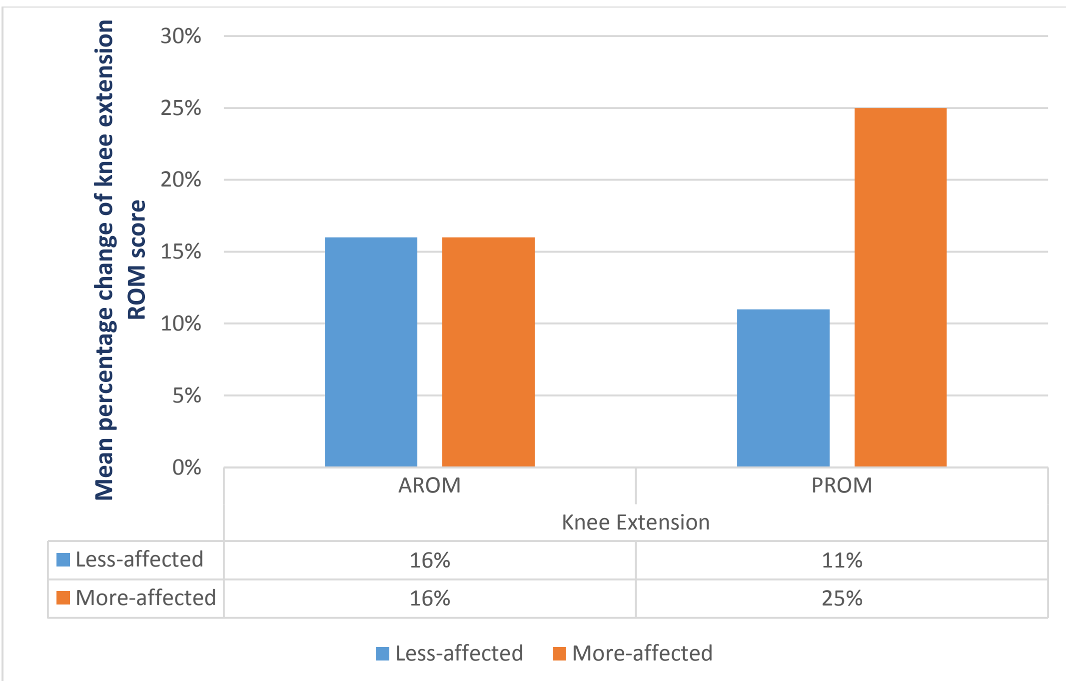


Figure 30. Knee extension ROM changes chart

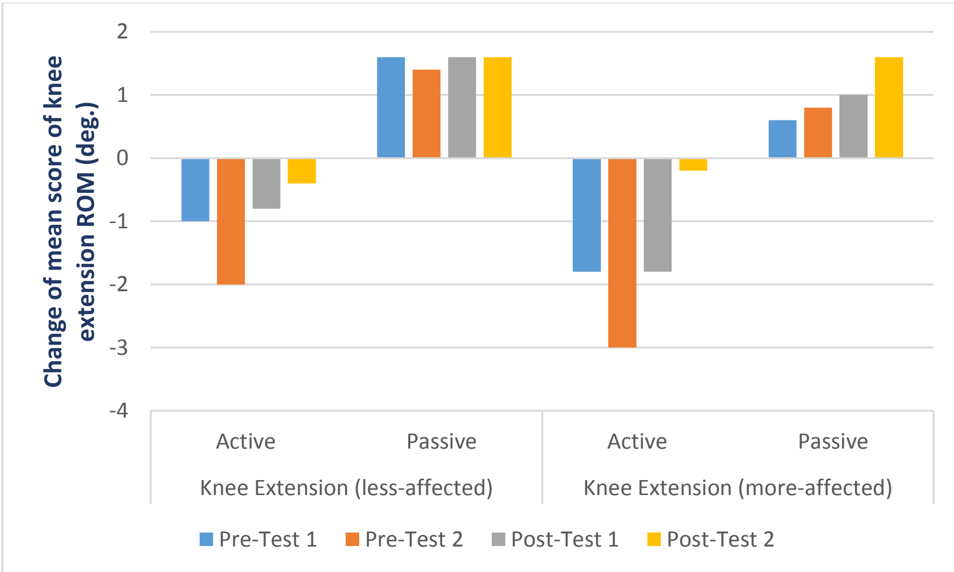


Figure 31. Change of knee extension ROM mean score prior to and after training

ROM: Knee Flexion. The mean score of active ROM of the less-affected knee flexors increased from 136.40°± 8.64° to 143.60° ± 4.72° at 1 week post training. However, it declined at 1 month follow up to 138.20° ± 5.02°, a 2% improvement (Table 40 & Figure 32). A repeated measures ANOVA showed no statistically significant difference between mean scores ($F(2.10, 8.40) = 2.16$, $p = .173$). Post hoc tests revealed no statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = .570$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = .769$) (Table 41 & Figure 33). At the same time point, the mean score of active ROM of the more-affected knee flexors had significantly increased from 128.80° ± 6.38° to 142.20° ± 3.83°; however it declined at 1 month follow up to 132.40 ± 9.73°, a 3% improvement (Table 40 & Figure 32). A repeated measures ANOVA showed a statistically significant difference between different time points ($F(2.03, 8.14) = 9.66$, $p = .007$). Post hoc tests using the Bonferroni correction revealed statistically significant differences on mean score between baseline and immediate training ($p = .009$). No statistically significant changes were seen between initial and baseline (p = .211), initial and immediate training (p = .729), initial and follow up (p=1), baseline and follow up (p = .652), and immediate training and follow up (p = .222) (Table 41 & Figure 33).

The mean score of passive ROM of the less-affected knee flexors slightly increased from 146.40° ± 5.50° to 147.60° ± 6.34° at 1 week post-training; however, the mean score of passive ROM declined at one month follow up to 146.60° ± 7.26° (Table 40 & Figure 32). A repeated measures ANOVA did not show a statistically significant difference between different time points (F(1.18, 4.74) = .081, p = .827). Post hoc tests using the Bonferroni correction revealed no statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = .534) (Table 41 & Figure 33). The mean score of passive ROM of the more-affected knee flexors did not show any significant improvement based on repeated measures ANOVA results (F(1.51, 6.05) = 2.07, p = .205) (Table 40 & Figure 32). Post hoc tests using the Bonferroni correction showed statistically significant differences on mean score between baseline and immediate training (p = .001). No statistically significant changes were seen between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and follow up (p = .553), and immediate training and follow up (p = 1) (Table 41 & Figure 33).

Table 40. Mean ± SD knee flexion ROM (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
Active (LA) knee flexion	142.40± 6.10	136.40± 8.64	143.60 ± 4.72	138.20 ± 5.02	2.16	2.10, 8.40	.173
Active (MA) knee flexion	135.80 ± 7.15	128.80 ± 6.38	142.20 ± 3.83	132.40 ± 9.73	9.66	2.03, 8.14	.007*
Passive (LA) knee flexion	147.20 ± 7.15	146.40 ± 5.50	147.60 ± 6.34	146.60 ± 7.26	.081	1.18, 4.74	.827
Passive (MA) knee flexion	143.80 ± 7.88	138.40 ± 5.17	145.40 ± 4.98	143.20 ± 7.72	2.07	1.51, 6.05	.205

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 41. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
Active (LA) knee flexion	1	1	1	.570	1	.769
Active (MA) knee flexion	.211	.729	1	.009*	.652	.222
Passive (LA) knee flexion	1	1	1	1	1	.534
Passive (MA) knee flexion	1	1	1	.001*	.553	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

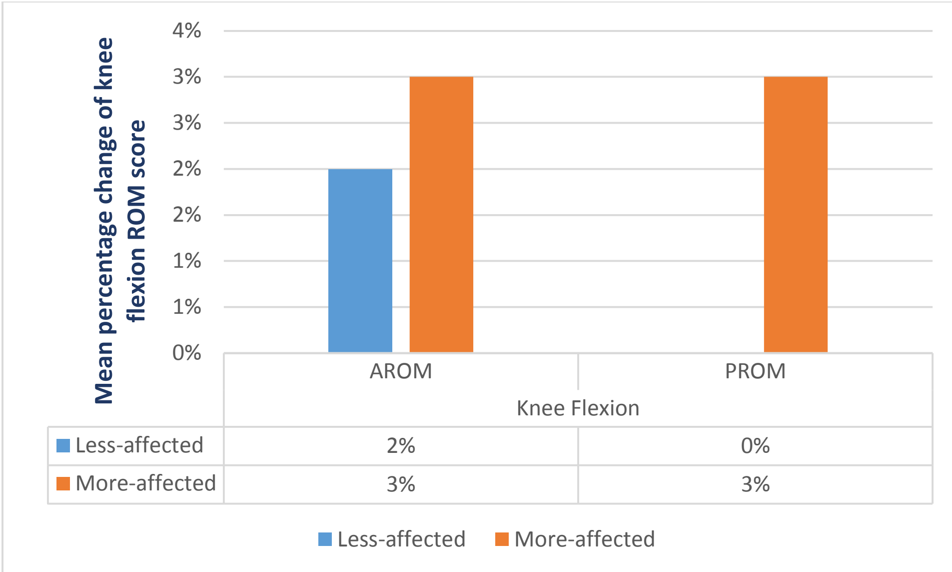


Figure 32. Knee flexion ROM changes chart

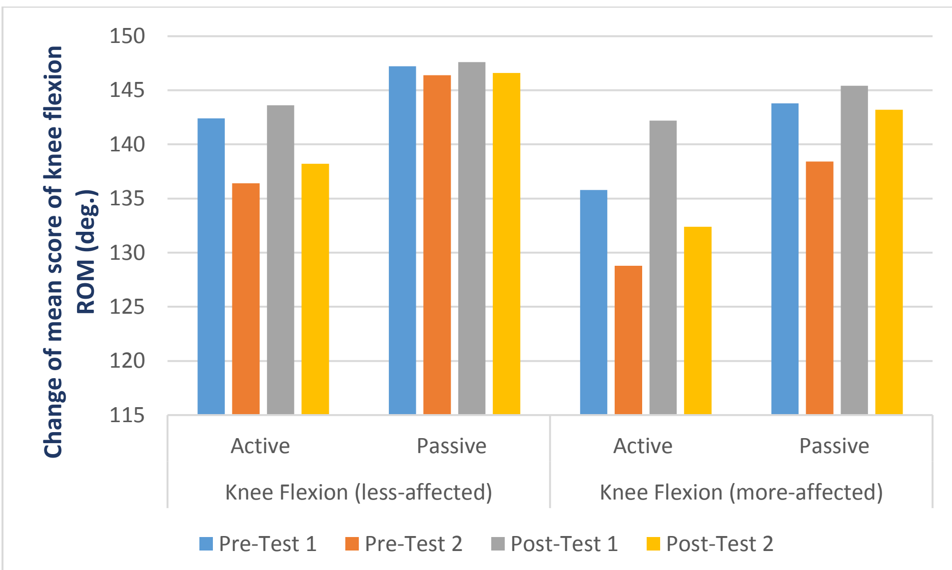


Figure 33. Change of knee flexion ROM mean score prior to and after training

ROM: Hip Abduction. The mean score of active ROM of the less-affected hip abductors showed no significant improvement across time points (F(1.90, 7.62) = .262, p = .767) (Table 42 & Figure 34). Post hoc tests using the Bonferroni correction did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 43 & Figure 35). The mean score of active ROM of the more-affected hip abductors showed no significant improvement (F(1.88, 7.54) = .580, p = .574) (Table 42 & Figure 34). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 43 & Figure 36).

By 1 month follow up, the mean score of passive ROM of the less-affected hip abductors increased from 39.20°± 12.31° to 45°± 11.22°, a 21% improvement (Table 42 & Figure 34). A repeated measures ANOVA did not show a statistically significant difference between different time points (F(1.25, 5.01) = .877, p = .419). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=.499), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 43 & Figure 35). The mean score of passive ROM of the more-affected hip abductors, by 1 month follow up, increased from 37°± 8.21° to 42.20°± 7.69°, an improvement of 16% (Table 42 & Figure 34). A repeated measures ANOVA showed no statistically significant difference between different time points (F(1.81, 7.27) = 1.75, p = .239). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = .866), baseline and follow up (p = .671), and immediate training and follow up (p = 1) (Table 43 & Figure 36).

Table 42. Mean ± SD hip abduction (AB) ROM (deg.) changes prior to and after training

	Initial baseline	Baseline	Immediate training	Follow up	F	df	p-value
Active (LA) hip AB	36.40± 10.50	34± 10.58	37.20± 10.47	36.20± 13.42	.262	1.90, 7.62	.767
Active (MA) hip AB	32.60± 6.98	29.20± 12.98	33.40± 10.76	34.20± 9.33	.580	1.88, 7.54	.574
Passive (LA) hip AB	41.80± 10.71	39.20± 12.31	43.40± 9.31	45± 11.22	.877	1.25, 5.01	.419
Passive (MA) hip AB	38.80± 8.07	37± 8.21	42.20± 7.22	42.20± 7.69	1.75	1.81, 7.27	.239

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 43. Post hoc test showed the difference between time points

p-value	Initial and baseline	Initial and immediate training	Initial and follow up	Baseline and immediate training	Baseline and follow up	Immediate training and follow up
Active (LA) hip AB	1	1	1	1	1	1
Active (MA) hip AB	1	1	1	1	1	1
Passive (LA) hip AB	1	1	.499	1	1	1
Passive (MA) hip AB	1	1	1	.866	.671	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

ROM: Hip Adduction. The mean score of active ROM of the less-affected hip adductors improved by 1 week post-training, from 22.60°± 6.54° to 25.40°± 6.14°. An even bigger improvement occurred at 1 month follow up with the mean score of active ROM increasing to 27.80°± 4.26°, a 30% improvement (Table 44 & Figure 34). A repeated measures ANOVA did not show any statistically significant differences between different time points (F(1.77, 7.10) = 1.35, p = .312). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p

= 1) (Table 45 & Figure 35). By 1 week post-training, there was a slight improvement in the mean score of active ROM of the more-affected hip adductors from 18.80°± 6.68° to 23.60°± 6.10°, and to 26°± 4° by one month follow up (56% improvement) (Table 44 & Figure 34). However, that improvement was not statistically significant ($F(1.19, 4.77) = 3.52$, $p = .121$). Post hoc tests revealed statistically significant differences on mean score between initial and follow up ($p=.018$). No statistically significant changes were seen between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), baseline and immediate training ($p = .108$), baseline and follow up ($p = .532$), and immediate training and follow up ($p = 1$) (Table 45 & Figure 36).

The mean score of passive ROM of the less-affected hip adductors increased from 28.60°± 7.53° to 33°± 6.08° at 1 month follow up, a 21% improvement (Table 44 & Figure 34). A repeated measures ANOVA showed no statistical significance between different time points ($F(1.25, 5.02) = 2.32$, $p = .191$). Post hoc tests using the Bonferroni correction did not reveal any statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = .347$), initial and follow up ($p=.341$), baseline and immediate training ($p = .349$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 45 & Figure 35). The mean score of passive ROM of the more-affected hip adductors increased from 25.80°± 8.58° to 27.80°± 6.34° at 1 week post-training, and to 31°± 6.40° at 1 month follow up, a 28% improvement (Table 44 & Figure 34). A repeated measures ANOVA did not show any statistical significance between different time points ($F(1.67, 6.68) = 2$, $p = .208$). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up (p=.494), baseline and immediate training (p = .775), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 45 & Figure 36).

Table 44. Mean ± SD hip adduction (ADD) ROM (deg.) changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
Active (LA) hip ADD	24.40± 6.18	22.60± 6.54	25.40± 6.14	27.80± 4.26	1.35	1.77, 7.10	.312
Active (MA) hip ADD	21± 5.38	18.80± 6.68	23.60± 6.10	26± 4	3.52	1.19, 4.77	.121
Passive (LA) hip ADD	27.40± 4.56	28.60± 7.53	31.60± 6.06	33± 6.08	2.32	1.25, 5.02	.191
Passive (MA) hip ADD	26± 4.18	25.80± 8.58	27.80± 6.34	31± 6.40	2	1.67, 6.68	.208

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 45. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
Active (LA) hip ADD	1	1	1	1	1	1
Active (MA) hip ADD	1	1	.018*	.108	.532	1
Passive (LA) hip ADD	1	.347	.341	.349	1	1
Passive (MA) hip ADD	1	1	.494	.775	1	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

ROM: Hip Extension. The mean score of active ROM of the less-affected hip extensors showed no significant improvement (F(1.17, 4.70) = .158, p = .747) (Table 46 & Figure 34). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 47 & Figure 35). The mean score of active ROM of the more-affected hip extensors slightly improved from 10.60°± 6.91° to 12.20°± 4.26° (61% improvement) at 1 month follow up (Table 46 & Figure 34). However, the improvement was not statistically significant ($F(1.55, 6.21) = .457$, $p = .607$). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 47 & Figure 36).

Slight improvement in the mean score of passive ROM of the less-affected hip extensors occurred at 1 month follow up, improving from 24.60°± 8.82° to 25.80°± 4.60° (18% improvement) (Table 46 & Figure 34). A repeated measures ANOVA did not show a statistically significant difference between different time points ($F(2.04, 8.18) = .439$, $p = .663$). Post hoc tests did not reveal any statistically significant differences on mean score between time initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 47 & Figure 35). At 1 month follow up, the mean score of passive ROM of the more-affected hip extensor increased from 22°± 8.80° to 24.40°± 3.57°, an 28% improvement, but this was not statistically significant ($F(1.73, 6.94) = 1.30$, $p = .324$) (Table 46 & Figure 34). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = .596$) (Table 47 & Figure 36).

Table 46. Mean ± SD hip extension (EX) ROM (deg.) changes prior to and after training

	Initial baseline	Baseline	Immediate training	Follow up	F	df	p-value
Active (LA) hip Ex	10.80± 12.37	12± 8.09	12± 7.34	12.20± 6.97	.158	1.17, 4.70	.747
Active (MA) hip Ex	9.40± 11.61	10.60± 6.91	11.60± 5.22	12.20± 4.26	.457	1.55, 6.21	.607
Passive (LA) hip Ex	23.80± 7.39	24.60± 8.82	26± 6.96	25.80± 4.60	.439	2.04, 8.18	.663
Passive (MA) hip Ex	20.20± 7.72	22± 8.80	23.60± 4.03	24.40± 3.57	1.30	1.73, 6.94	.324

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 47. Post hoc test showed the difference between time points

p-value	Initial and baseline	Initial and immediate training	Initial and follow up	Baseline and immediate training	Baseline and follow up	Immediate training and follow up
Active (LA) hip Ex	1	1	1	1	1	1
Active (MA) hip Ex	1	1	1	1	1	1
Passive (LA) hip Ex	1	1	1	1	1	1
Passive (MA) hip Ex	1	1	1	1	1	.596

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

ROM: Hip Flexion. The mean score of active ROM of the less-affected hip flexors increased from 110.60°± 12.64° to 115°± 11.26° at 1 week post-training, and to 116.40°± 9.83° at 1 month follow up, improving 6% (Table 48 & Figure 34). A repeated measures ANOVA did not show a statistically significant difference between different time points (F(1.58, 6.33) = 1.12, p = .366). Post hoc tests using the Bonferroni correction revealed no statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = .177), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 49 & Figure 35). At 1 week post-training, the mean score of active ROM of the more-affected hip flexors increased from 106°± 11.42° to 115.20°± 9.52°, and at 1 month follow up, improved 6% increasing to 112°± 7.48° (Table 48 & Figure 34). A repeated measures ANOVA showed no statistically significant difference between different time points ($F(1.90, 7.63) = 2.16$, $p = .181$). Post hoc tests showed statistically significant differences on mean score between baseline and immediate training ($p = .029$). No statistically significant changes were seen between initial and baseline ($p = 1$), initial and immediate training ($p = .645$), initial and follow up ($p=1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 49 & Figure 36).

There was a slight improvement (1%) in the mean score of passive ROM of the less-affected hip flexors from 126.60°± 9.04° to 128°± 13.92° at 1 month follow up (Table 48 & Figure 34). However, the improvement was not statistically significant ($F(1.48, 5.92) = .963$, $p = .406$). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline ($p = .258$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 49 & Figure 35). The mean score of passive ROM of the more-affected hip flexors, by 1 month follow up, increased from 122°± 9.19° to 125.40°± 9.99°, a 3% improvement (Table 48 & Figure 34). However, the improvement was not statistically significant ($F(2.19, 8.75) = 1.09$, $p = .381$). Post hoc tests revealed no statistically significant differences on mean score between time initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 49 & Figure 36).

Table 48. Mean ± SD hip flexion (FX) ROM (deg.) changes prior to and after training

	Initial baseline	Baseline	Immediate training	Follow up	F	df	p-value
Active (LA) hip Fx	110.80± 10.03	110.60± 12.64	115± 11.26	116.40± 9.83	1.12	1.58, 6.33	.366
Active (MA) hip Fx	105.60± 6.26	106± 11.42	115.20± 9.52	112± 7.48	2.16	1.90, 7.63	.181
Passive (LA) hip Fx	122.20± 8.10	126.60± 9.04	125.80± 13.64	128± 13.92	.963	1.48, 5.92	.406
Passive (MA) hip Fx	119.60± 8.79	122± 9.19	124.40± 11.26	125.40± 9.99	1.09	2.19, 8.75	.381

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 49. Post hoc test showed the difference between time points

p-value	Initial and baseline	Initial and immediate training	Initial and follow up	Baseline and immediate training	Baseline and follow up	Immediate training and follow up
Active (LA) hip Fx	1	1	1	.177	1	1
Active (MA) hip Fx	1	.645	1	.029*	1	1
Passive (LA) hip Fx	.258	1	1	1	1	1
Passive (MA) hip Fx	1	1	1	1	1	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

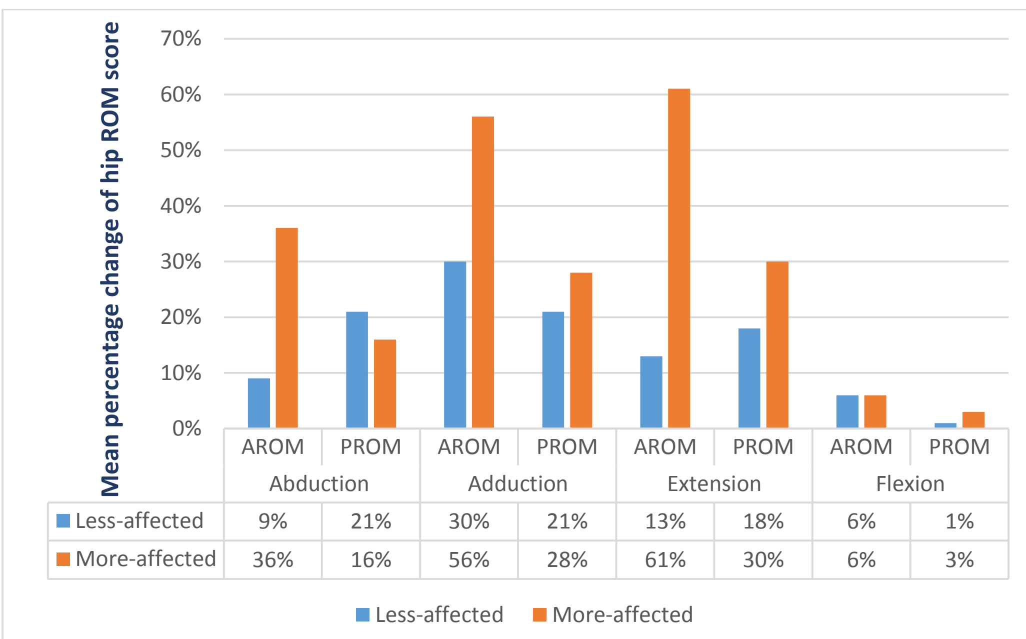


Figure 34. Hip ROM improvement chart

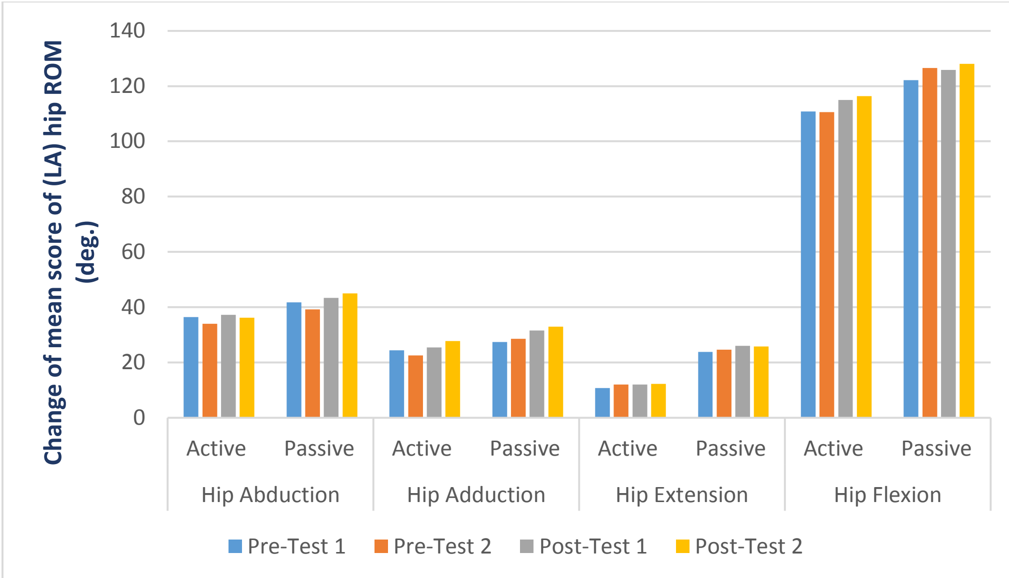


Figure 35. Change of (LA) hip ROM mean score prior to and after training

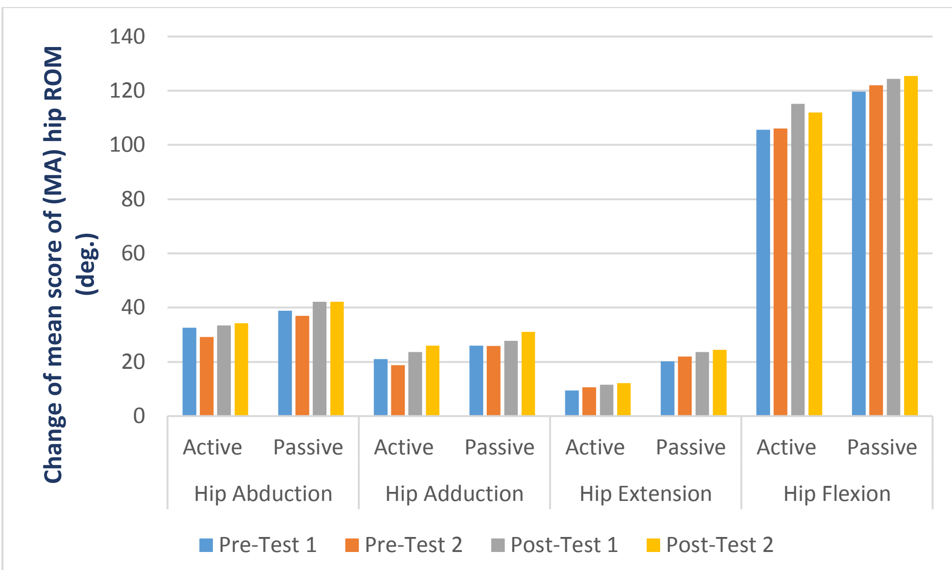


Figure 36. Change of (MA) hip ROM mean score prior to and after training

Ankle Control and Coordination

Data from the Boyd and Graham Selective Motor Control test were analyzed for all four time points, and the results revealed that the mean score of less-affected ankle dorsiflexion control increased from 3.20± .447 to 3.80± .447 at 1 month follow up, a 20% improvement (Table 50 & Figure 37). A repeated measures ANOVA revealed a statistically significant difference between different time points (F(1.71, 6.85) = 8.50, p = .016). Post hoc tests did not reveal any statistically significant differences on mean score between initial and baseline (p = 1), initial and immediate training (p = .097), initial and follow up (p=.079), baseline and immediate training (p = .423), baseline and follow up (p = .423), and immediate training and follow up (p = 1) (Table 51 & Figure 38).

By 1 month follow up, the mean score of more-affected ankle dorsiflexion control statistically increased from 2± .707 to 2.80± .837, a 47% improvement (Table 50 & Figure 37). A repeated measures ANOVA showed a statistically significant difference between different time points (F(1.55, 6.20) = 16, p = .004). Post hoc tests revealed statistically significant differences on mean score between initial and immediate training (p = .023). No significant differences were seen between initial and baseline (p = 1), initial and follow up (p=.205), baseline and immediate training (p = 1), baseline and follow up (p = .097), and immediate training and follow up (p = 1) (Table 51 & Figure 38).

Table 50. Mean ± SD Boyd and Graham Selective Motor Control test changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**
(LA) ankle control	3 ± .707	3.20± .447	3.80± .447	3.80± .447	8.50	1.71, 6.85	.016*
(MA) ankle control	1.80± .837	2± .707	3± .707	2.80± .837	16	1.55, 6.20	.004*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

Table 51. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
p-value ((LA) ankle control)	1	.097	.097	.423	.423	1
p-value ((MA) ankle control)	1	.023*	.205	1	.097	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

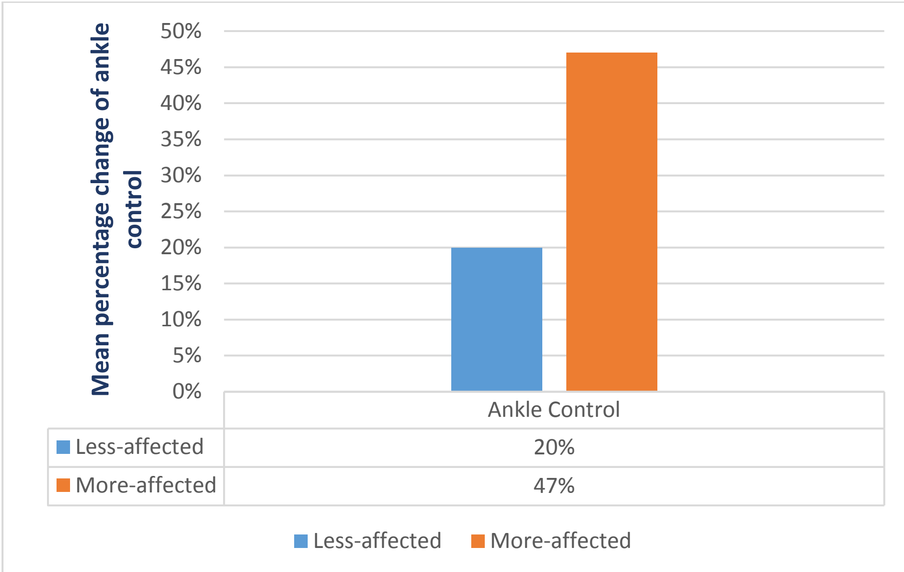


Figure 37. Ankle control improvement chart

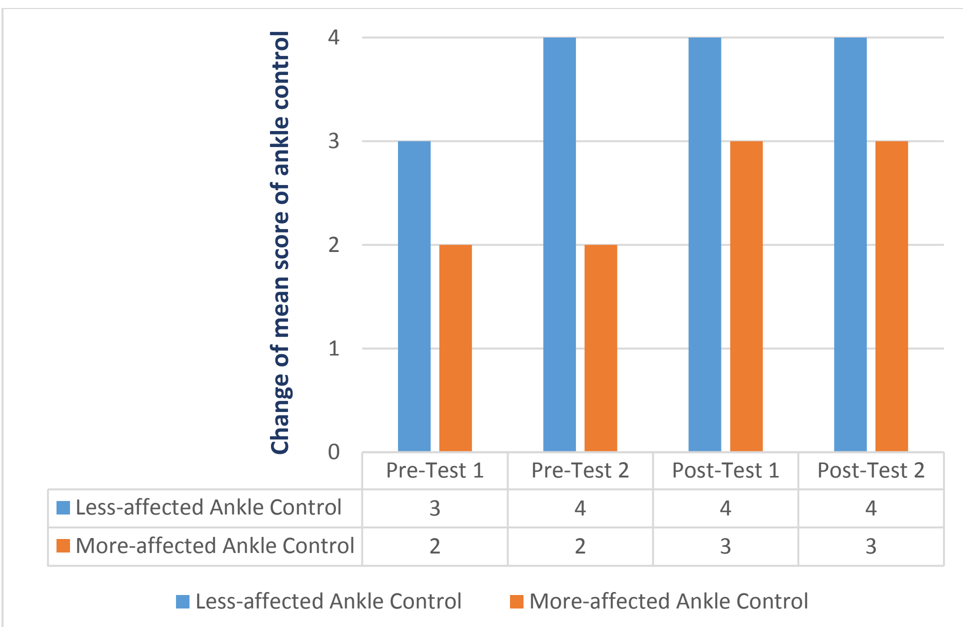


Figure 38. Change of Boyd and Graham Selective Motor Control mean score prior to and after training

Ankle Performance

Ankle Performance: Accuracy (distance from target). The robotic data analysis showed a significant decrease in the distance from the target in the less-affected ankle from 17.41 mm ± 2.24 mm to 7.21 mm ± 2.06 mm, a 58% decline, and for the more-affected leg from 25.04 mm ± 8.77 mm to 11.36 mm ± 3.32 mm, a 54% decline (Table 52 & Figure 39). A decrease in distance indicates an improvement in the accuracy of the movement. A repeated measures ANOVA showed a statistically significant difference between initial and final training sessions for less-affected and more-affected leg accuracy ($F(1, 4) = 44.78$, $p = .003$), ($F(1, 4) = 28.02$, $p = .006$) (Figure 40).

Ankle Performance: Smoothness (how rough was the patient's motion). The results showed a significant decrease in jerkiness of the bilateral (less/more-affected) legs, from 85.93%± 3.96% to 71.53%± 5.20% (17% decline) and 87.79%± 8.40% to 73.63%± 6.02% (16% decline), respectively (Table 52 & Figure 39). A decrease in jerkiness indicates an improvement in the smoothness of the movement. A repeated measures ANOVA showed a statistically significant difference between initial and final training sessions for bilateral (less/more-affected) leg smoothness ($F(1, 4) = 20.29$, $p = .011$), ($F(1, 4) = 13.28$, $p = .022$) (Figure 40).

Table 52. Mean ± SD ankle accuracy (mm) and smoothness (%) changes prior to and after training

	Initial session	**Final session**	**F**	**df**	**p-value**
(LA) ankle accuracy	17.41± 2.24	7.21± 2.06	44.78	1,4	.003*
(MA) ankle accuracy	25.04± 8.77	11.36± 3.32	28.02	1,4	.006*
(LA) ankle smoothness	85.93± 3.96	71.53± 5.20	20.29	1,4	.011*
(MA) ankle smoothness	87.79± 8.40	73.63± 6.02	13.28	1,4	.022*

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

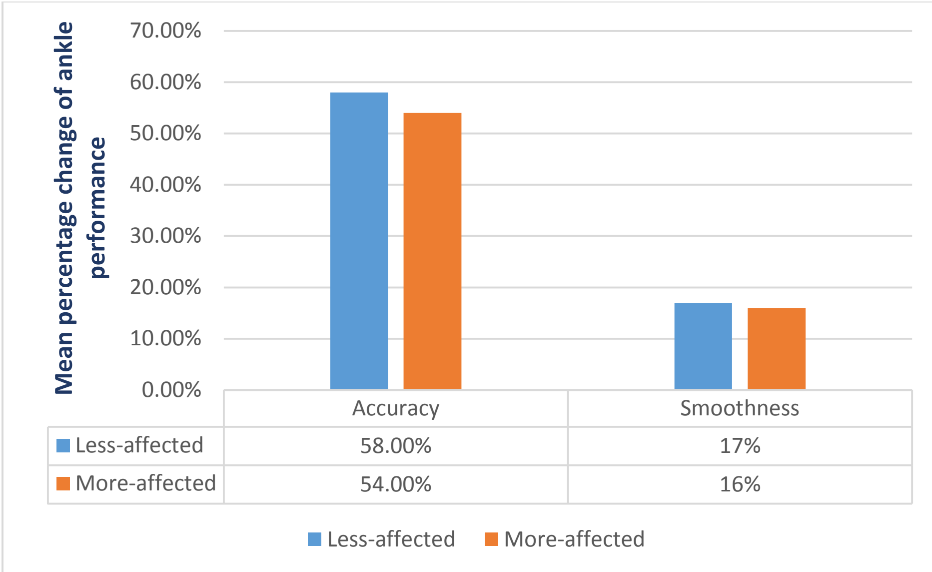


Figure 39. Ankle performance improvement chart

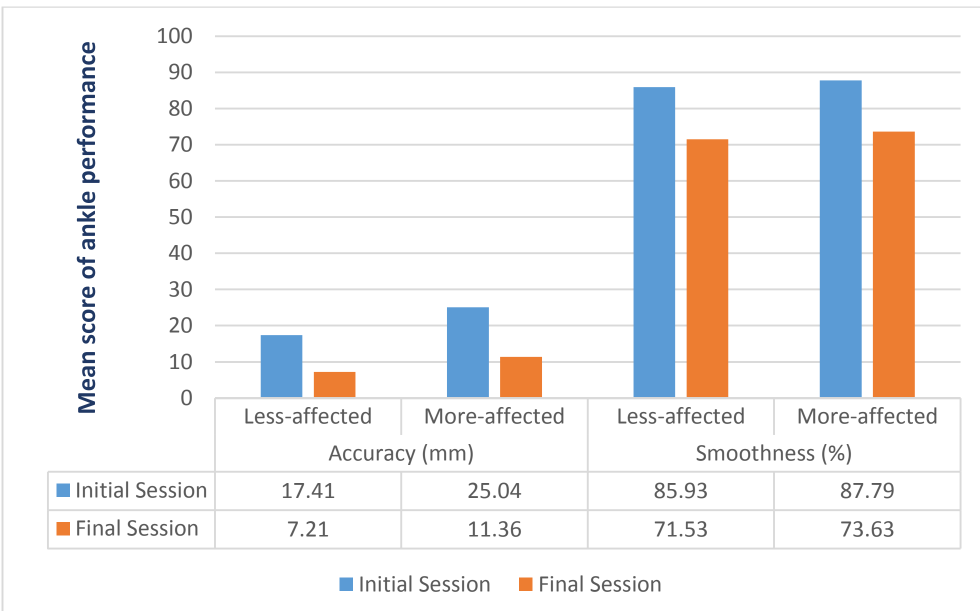


Figure 40. Change of ankle performance mean score prior to and after training

Balance

The data for the PBS was analyzed for all five subjects at all four time points. Table 53 illustrates the changes in scores over the course of study.

Table 53. Change in PBS balance scores prior to and after training

Subject	Initial baseline (points)	Baseline (points)	Immediate training (points)	Follow up (points)	Percentage changes (between baseline and follow up)
1	4	5	14	15	200%
2	50	50	56	56	12%
3	49	50	55	55	10%
4	48	48	54	55	14.4%
5	49	49	52	51	4.08%
Mean ± SD	40±20.13	40.40±19.80	46.20±18.06	46.40±17.65	48%
F	24.30				
df	1.04, 4.19				
P-value	<.007*				

*. Significant difference pre to post (p<.05).

Subject one improved from 5 to 15 over the course of study, a total change score of 10. Subject two improved from 50 to 56, a change score of 6. Subject three improved from 50 to 55, a change score of 5. Subject four improved from 48 to 55, a change score of 7. Lastly, subject five improved from 49 to 51, a total change score of 2. These scores indicate meaningful change over time when compared to the minimum detectable change score of 1.59 and minimum clinically important difference score of 5.83 (Chen et al., 2012) in CP patients. In general, all participants showed significant improvement in balance at 1 month follow up, ranging from 4.08%–200% with an overall 48% improvement in balance score, comparing to the baseline testing. However, there was greater improvement for the child with baseline balance impairment (BBS ≤ 5; mean BBS increase of 10 points) (Table 7).

A one-way repeated measured analysis of variance (ANOVA) was conducted to evaluate the change in scores. The results of ANOVA with a Greenhouse-Geisser correction determined that the mean balance score differed significantly between time points ($F(1.048, 4.191) = 24.306$, $p = 0.007$) (Table 54).

Post hoc tests using the Bonferroni correction revealed that the training elicited a slight improvement in balance score between initial and immediate training (40 ± 20.137 to 46.20 ± 18.061), which was statistically significant (p = .031). The results also showed significant improvement in scores between baseline and immediate training (40.40 ± 19.80 vs. 46.20 ± 18.061, p = .024). No significant differences emerged between initial and baseline (p = 1), initial and follow up (p = .067), baseline and follow up (p = .060), or immediate training and follow up (p = 1). Therefore, we can conclude that the task-specific ankle training program (6 weeks) elicits a statistically significant improvement in balance after 1 week post-training. However, the lack of significance after 1 month follow up does not mean there was no effect. The means at 1 week and at 1 month follow up were about the same, but the correlations between time-points made the differences from one week, but not the differences from one month, statistically significant. Table 54 and Figure 41 illustrate the differences between time-points.

Table 54. Post hoc test showed the difference between time points

	Initial and baseline	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
p-value	1	.031*	.067	.024*	.060	1

*. Significant difference pre to post (p<.05).

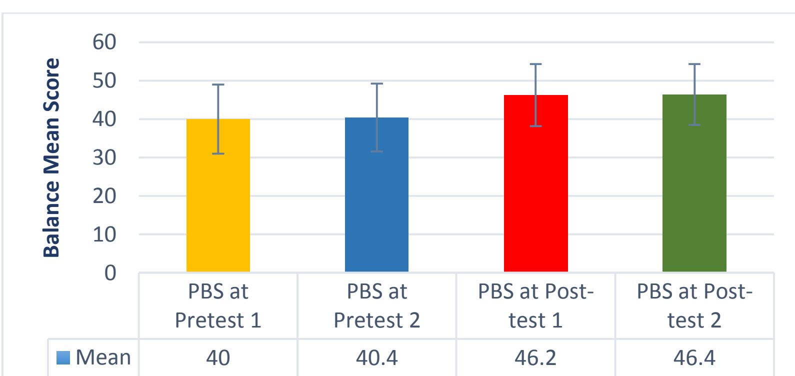


Figure 41. Change of the PBS mean score prior to and after training

2. Activity Level

The results revealed that, for outcome measures in activity level, there were no significant differences found between pretest one and two.

Gait Mechanics

Velocity. Data from the gait mat analysis were analyzed for all four time points, and the results showed that the mean velocity increased from 91.92 cm/sec ± 12.95 cm/sec to 105.07 cm/sec ± 21.42 cm/sec at 1 week post-training. Mean velocity then declined to 98.51 cm/sec ± 27.26 cm/sec at 1 month follow up, a 6% improvement (Table 55 & Figure 42). The more impaired subjects experienced the greatest gains in gait velocity. A repeated measures ANOVA failed to reveal any statistically significant difference between different time points ($F(2.05, 8.23) = 2.36$, $p = .154$). Post hoc tests using the Bonferroni correction did not reveal any statistically significant differences on mean velocity score between initial and baseline ($p = 1$), initial and immediate training ($p = .660$), initial and follow up ($p=.326$), baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 56 & Figure 43). Table 55 shows the summary of the ES statistics for velocity.

Step Length. Mean step length increased from 43.19 cm ±11.19 cm to 45.167 cm ±13.67 cm, increasing 4%, at 1 month follow up. Table 55 and Figure 42 depict the change in mean step length for each time point. A repeated measures ANOVA failed to reveal any statistically significant difference between different time points ($F(1.44, 5.77) = .903$, $p = .421$). Post hoc comparisons did not reveal any statistically significant differences on mean step length score between initial and baseline ($p = 1$), initial and immediate training ($p = 1$), initial and follow up ($p=1$), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 56 & Figure 43). Table 55 shows the summary of the ES statistics for step length.

Cadence. Mean cadence increased from 126.15 ± 11.53 to 130.51 ± 9.19 steps/min (4% increase) at 1month follow up. Table 55 and Figure 42 show the change in mean cadence for each time point. A repeated measures ANOVA did not reveal any statistically significant difference between different time points ($F(1.28, 5.15) = 2.139$, $p = .207$). Post hoc tests using the Bonferroni correction showed no statistically significant differences on mean cadence score between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=.500), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 56 & Figure 43). For all 5 participants' velocity, step length and cadence at follow up became more normal, as compared with reported data in normal velocity, step length and cadence in young children (Figure 44). Table 55 shows the summary of the ES statistics for velocity. Table 55 shows the summary of the ES statistics for cadence.

Stance and swing percentage. Mean stance duration decreased from 62.41% ± 3.94% to 61.75% ± 3.24%, a 1% decrease, at 1 month follow up. Table 55 and Figure 42 depict the change in mean stance percentage for each time point. A repeated measures ANOVA failed to reveal any statistically significant difference between different time points ($F(1.04, 4.19) = 1.03$, $p = .370$). Post hoc tests did not reveal any statistically significant differences on mean stance percentages between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 56 & Figure 43).

Mean swing duration increased for both paretic and non-paretic limbs, from 37.38% ± 3.80% to 38.23% ± 3.24% (2% increase) at 1 month follow up (Table 55 & Figure 42). A repeated measures ANOVA failed to reveal any statistically significant difference between different time points (F(1.05, 4.19) = 1.01, p = .374). Post hoc tests did not show any statistically significant differences on mean swing percentage scores between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p =.296), and immediate training and follow up (p = 1) (Table 56 & Figure 43). Although the change in mean score did not reach the significant level (p = .370, p = .374), the stance/swing ratio values moved toward normal for both limbs (Figure 45 & 46). In general, the more impaired subjects experienced the greatest gains in temporal measures. Table 55 shows the summary of the ES statistics for stance and swing duration.

Table 55. Mean ± SD gait parameters changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**	**ES**
Velocity (cm/sec)	78.11± 26.01	91.92± 12.95	105.07± 21.42	98.51± 27.26	2.362	2.05, 8.23	.154	1.2 [L]
Step length (cm)	41.96± 11.49	43.19± 11.19	45.48± 14.73	45.16± 13.67	.903	1.44, 5.77	.421	.7 [L]
Cadence (steps/min)	103.84± 33.47	126.15±11.53	120.13±17.82	130.51± 9.19	2.13	1.28, 5.15	.207	1.03 [L]
Stance%	68.55± 17.59	62.41± 3.94	61.98± 3.75	61.75± 3.24	1.03	1.04, 4.19	.370	.5 [M]
Swing%	31.43± 17.59	37.38±3.80	38.01±3.75	38.23± 3.24	1.01	1.05, 4.19	.374	.5 [M]

*. Significant difference pre to post (p<.05).
[L] ES of .80 or more =large effect
[M] ES of .50 = moderate effect
[S] ES of .20 = small effect

Table 56. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
p-value (velocity)	1	.660	.326	1	1	1
p-value (step length)	1	1	1	1	1	1
p-value (cadence)	1	1	.500	1	1	1
p-value (stance %)	1	1	1	1	1	1
p-value (swing%)	1	1	1	1	.296	1

*. Significant difference pre to post (p<.05).

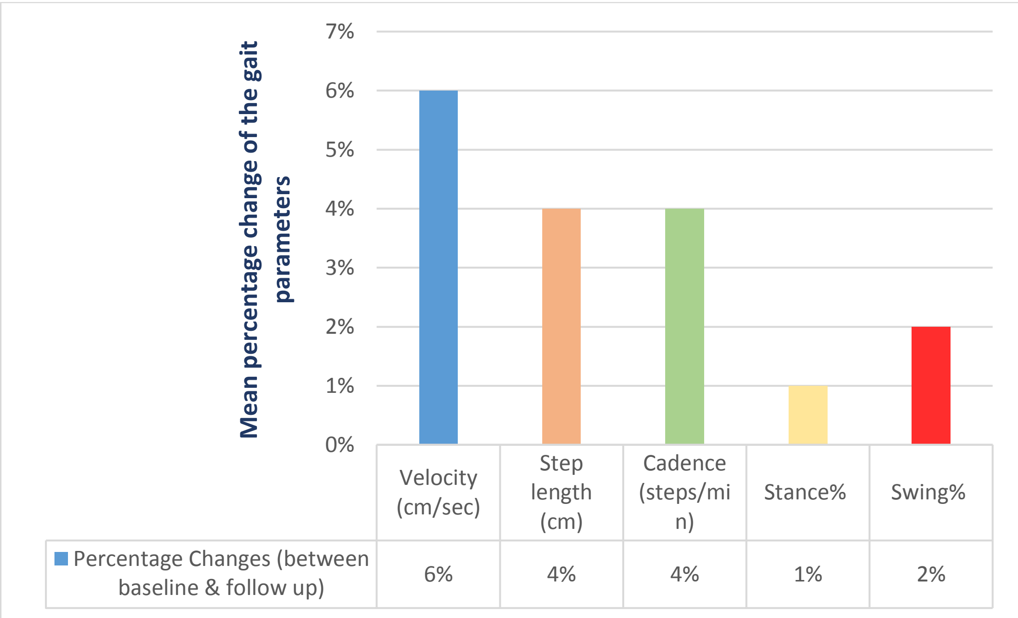


Figure 42. Gait parameters improvement chart

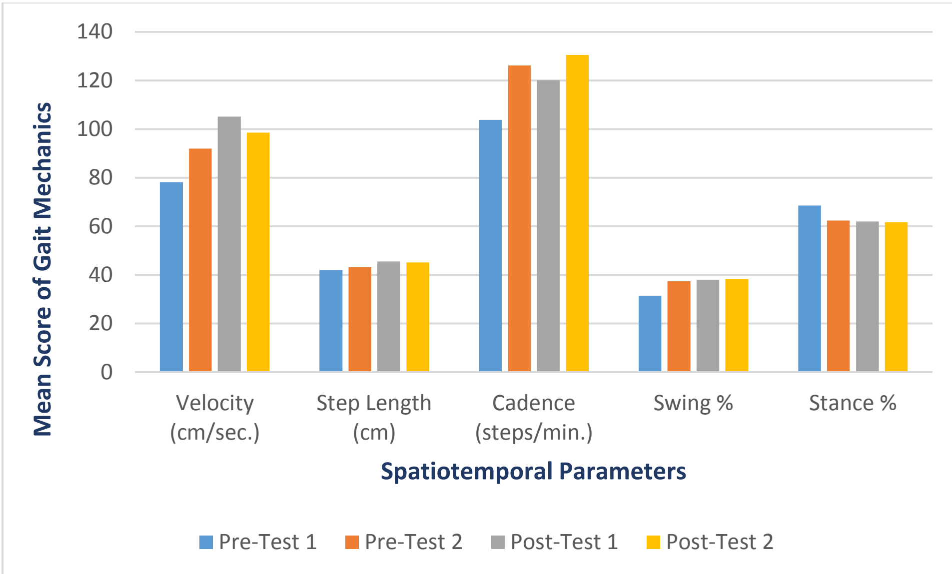
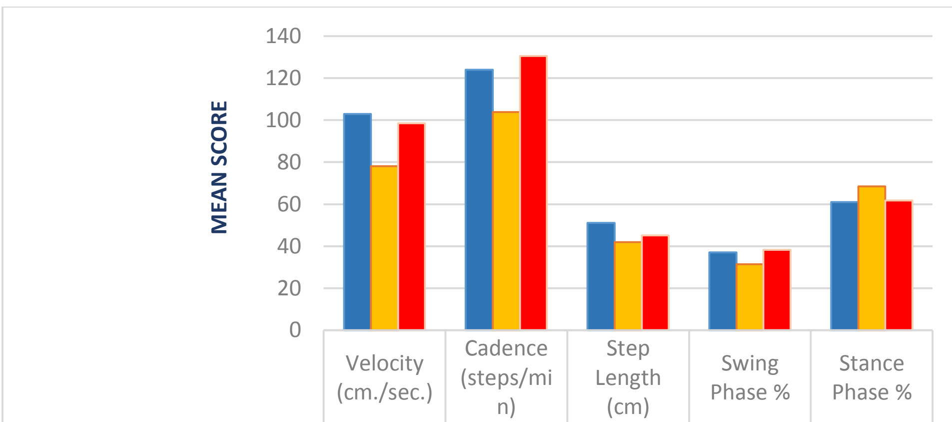


Figure 43. Change of gait mechanics mean score prior to and after training



	Velocity (cm./sec.)	Cadence (steps/min)	Step Length (cm)	Swing Phase %	Stance Phase %
Normal children (Dini & David, 2009)	103	124	51.14	37	61
Children with CP (pre1)	78.11	103.8436	41.96	31.43	68.55
Children with CP (post 2)	98.51	130.5112	45.16	38.23	61.75

Figure 44. Comparison of gait mechanics between normal children and children with CP

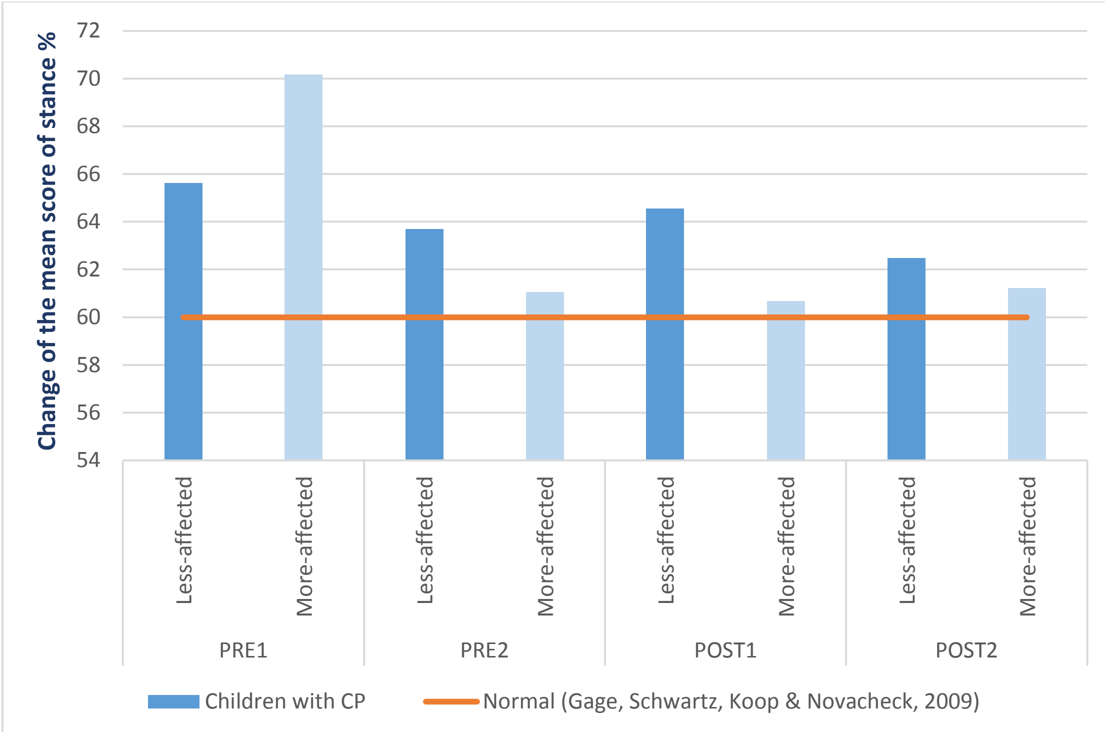


Figure 45. Comparison of stance % between normal children and children with CP

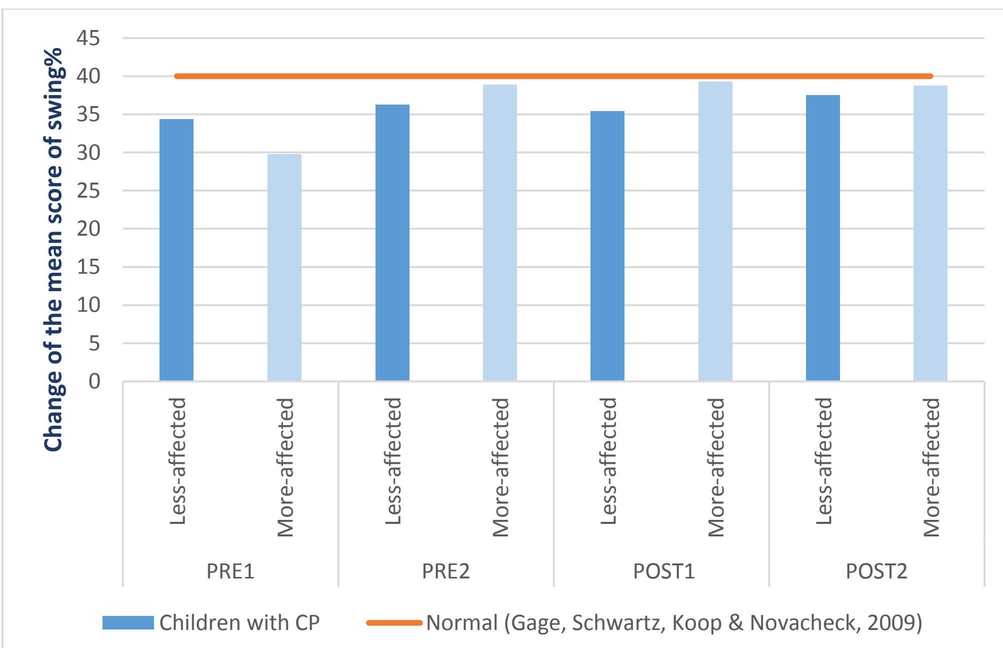


Figure 46. Comparison of swing % between normal children and children with CP

Single support percentage. Mean single support duration for the less-affected leg increased from 34.53% ± 13.54% to 41.02% ± 2.40%, a 5% increase, at 1 month follow up while more-affected leg increased from 32.80%± 9.50% to 37.88% ± 3.31%, a 12% increase. Table 57 depict the change in single support percentage for each time point. A repeated measures ANOVA failed to reveal any statistically significant difference between different time points for less-affected leg single support duration (F(1.09, 4.35) = 1.21, p = .334) and more-affected leg (F(1.18, 4.75) = .872, p = .416). Post hoc tests did not reveal any statistically significant differences on mean stance percentages of the less-affected leg between initial and baseline (p = 1), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1). Additionally, there is no statistical significant differences on mean single support percentages of the more-affected leg between initial and baseline (p = .607), initial and immediate training (p = 1), initial and follow up (p=1), baseline and immediate training (p = 1), baseline and follow up (p = 1), and immediate training and follow up (p = 1) (Table 58). The values moved toward normal (40%) for both limbs (Figure 47).

Table 57. Mean ± SD single support % changes prior to and after training

	Initial baseline	**Baseline**	**Immediate training**	**Follow up**	**F**	**df**	**p-value**	**ES**
(LA) leg single support%	34.53±13.54	39.11±3.48	39.67±3.28	41.02±2.40	1.21	1.09, 4.35	.334	.522[M]
(MA) leg single support%	32.80±9.50	35.20±7.35	36.13±2.10	37.88±3.31	.872	1.18, 4.75	.416	.515[M]

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.
[L] ES of .80 or more =large effect
[M] ES of .50 = moderate effect
[S] ES of .20 = small effect

Table 58. Post hoc test showed the difference between time points

p-value	**Initial and baseline**	**Initial and immediate training**	**Initial and follow up**	**Baseline and immediate training**	**Baseline and follow up**	**Immediate training and follow up**
p-value (LA) single support%)	1	1	1	1	1	1
p-value (MA) single support%)	.607	1	1	1	1	1

*. Significant difference pre to post (p<.05).
Note. (LA)= less-affected & (MA)= more-affected.

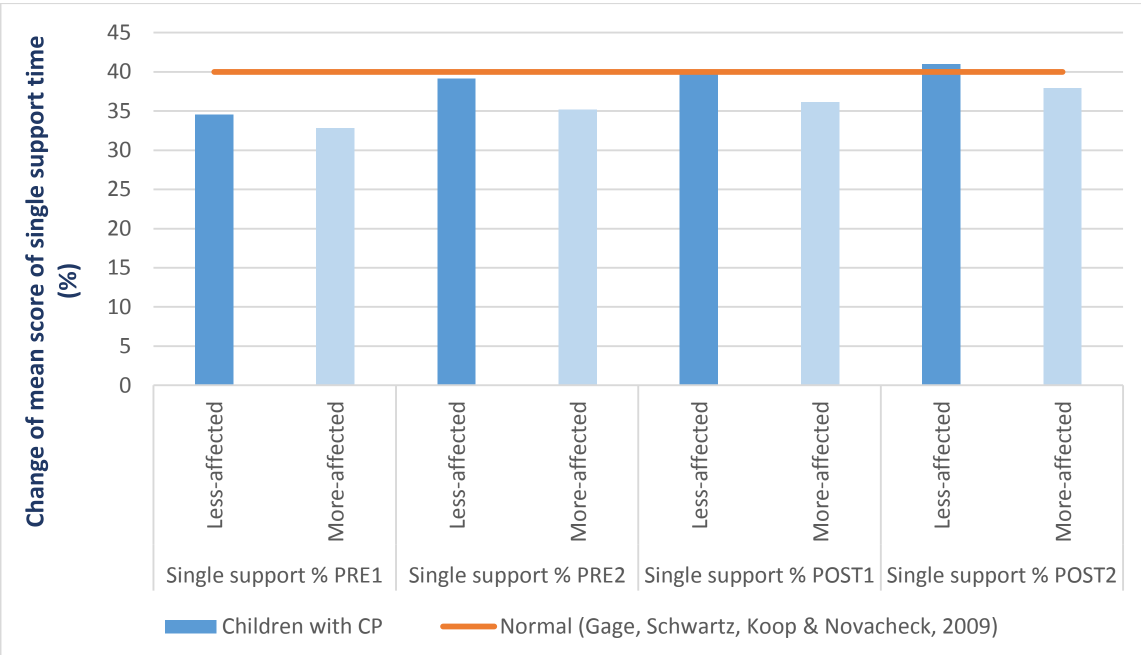


Figure 47. Comparison of Single support % between normal children and children with CP

Activity Count

EE spent in light and moderate physical activity. The result from the accelerometer showed no significant increase in EE spent in light physical activity, as seen by repeated measures ANOVA ($F(1.86, 7.45) = .132$, $p = .866$) (Table 59 & Figure 48). Post hoc tests failed to reveal any statistically significant differences between baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 60 & Figure 49). Similarly, there was no significant increase in EE spent in moderate physical activity. A repeated measures ANOVA failed to reveal any statistically significant difference between different time points ($F(1.65, 6.63) = .080$, $p = .894$) (Table 59 & Figure 48). Post hoc tests did not reveal any statistically significant differences between baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 60 & Figure 49).

EE spent in vigorous physical activity. The analysis also failed to show any significant increase in EE spent in vigorous physical activity. A repeated measures ANOVA did not reveal any statistically significant difference between different time points ($F(1.16, 4.63) = .366$, $p = .604$) (Table 59 & Figure 48). Post hoc tests showed no statistically significant differences between baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = .621$) (Table 60 & Figure 49). The analysis also showed that at 1 month follow up the EE spent on light, moderate and vigorous activities increased by 171%, 180% and 37%, respectively (Figure 48).

Total EE. The results showed 176% improvement in the mean score of total EE at 1 month follow up, increasing from 2143.48 (kcal/day) ± 1974.1(kcal/day) to 2532.16 (kcal/day) ± 1487.35 (kcal/day) (Table 49 & Figure 48). A repeated measures ANOVA failed to reveal any statistically significant difference between different time points ($F(1.73, 6.92) = .091$, $p = .890$). Post hoc tests did not reveal any statistically significant differences between baseline and immediate training ($p = 1$), baseline and follow up ($p = 1$), and immediate training and follow up ($p = 1$) (Table 60 & Figure 49).

Table 59. Mean ± SD EE changes prior to and after training

	Baseline	Immediate training	Follow up	F	df	p-value	ES
Light EE (kcal/ day)	829.88± 752.73	1053.42 ± 714.57	978.64 ± 518.48	.132	1.86, 7.45	.866	.146[S]
Moderate EE (kcal/ day)	1279.90 ± 1206.32	1507.89 ± 992.36	1534.78 ± 967.26	.080	1.65, 6.63	.894	.152[S]
Vigorous EE (kcal/ day)	33.68±44.53	38.51±42.64	18.73± 14.09	.366	1.16, 4.63	.604	-.286[S]
Total EE (kcal/ day)	2143.48±1974.10	2599.83±1703.53	2532.16± 1487.35	.091	1.73, 6.92	.890	.143[S]

*. Significant difference pre to post (p<.05).
[L] ES of .80 or more =large effect
[M] ES of .50 = moderate effect
[S] ES of .20 = small effect

Table 60. Post hoc test showed the difference between time points

p-value	Baseline and immediate training	Baseline and follow up	Immediate training and follow up
p-value (EE light)	1	1	1
p-value (EE mod)	1	1	1
p-value (EE vig)	1	1	.621
p-value (total EE)	1	1	1

*. Significant difference pre to post (p<.05).

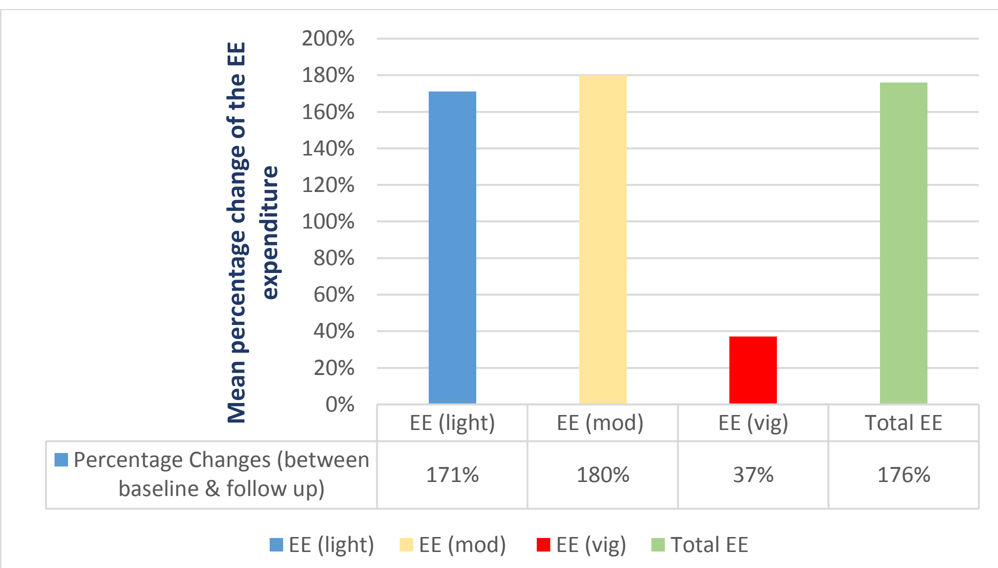


Figure 48. Percentage changes of EE (between baseline and follow up)

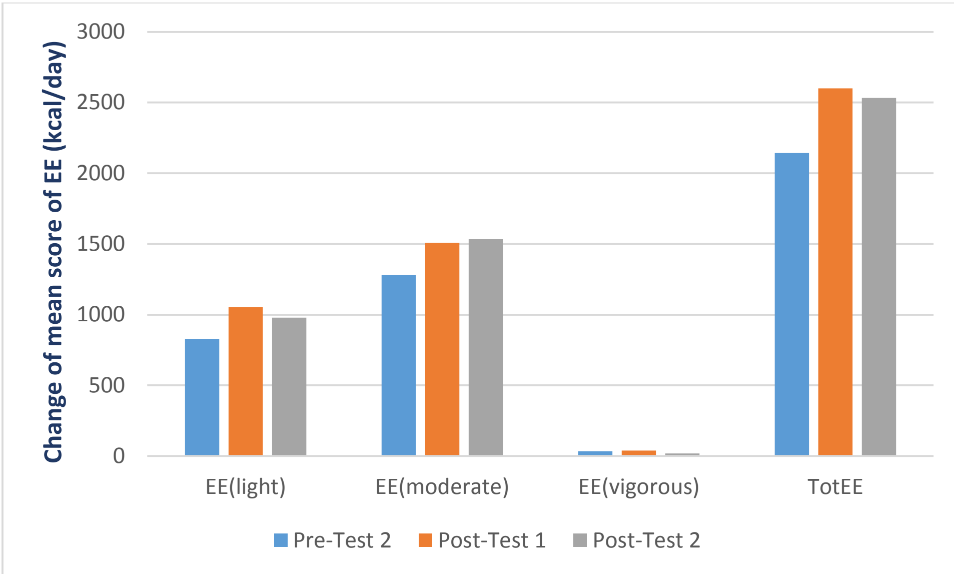


Figure 49. Change of energy expenditure mean score prior to and after training

Number of steps. There was a 93% improvement in the number of steps (40772 ± 24029.8 to 62893.80 ± 19553.9) (Table 61 & Figure 50). A repeated measures ANOVA failed to reveal any statistically significant difference between different time points (F(1.54, 6.19) = 2.97, p = .129). Post hoc tests did not reveal any statistically significant differences between baseline and immediate training (p = .336), baseline and follow up (p = .306), and immediate training and follow up (p = 1) (Table 62 & Figure 51). Table 61 shows the summary of the ES statistics for number of steps per day.

TAC. There was a 197% improvement in the TAC (1348153.40 ± 878892.2 to 1872413 ± 517560.1) at 1 month follow up (Table 61 & Figure 50). A repeated measures ANOVA failed to reveal any statistically significant difference between different time points (F(1.26, 5.06) = 1.3, p = .322). Post hoc tests failed to reveal any statistically significant differences between baseline and immediate training (p = .873), baseline and follow up (p = .929), and immediate training and follow up (p = 1) (Table 62 & Figure 52). Table 61 shows the summary of the ES statistics for TAC.

Table 61. Mean ± SD number of steps and TAC changes prior to and after training

	Baseline	Immediate training	Follow up	F	df	p-value	ES
Number of steps	40772± 24029.83	76692.40± 35913.27	62893.80± 19553.91	2.97	1.54, 6.19	.129	.5 [M]
TAC	1348153.40±878892.25	2314520.60±1251180.33	1872413± 517560.17	1.30	1.26, 5.06	.322	.9 [L]

*. Significant difference pre to post (p<.05).
[L] ES of .80 or more =large effect
[M] ES of .50 = moderate effect
[S] ES of .20 = small effect

Table 62. Post hoc test showed the difference between time points

p-value	Baseline and immediate training	Baseline and follow up	Immediate training and follow up
p-value (number of steps)	.336	.306	1
p-value (TAC)	.873	.929	1

*. Significant difference pre to post (p<.05).

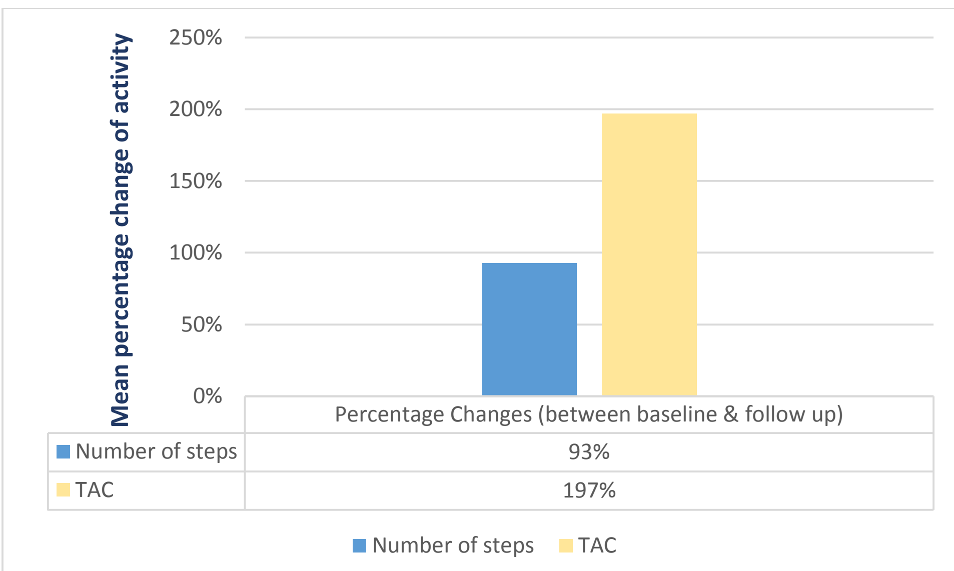


Figure 50. Activity improvement chart

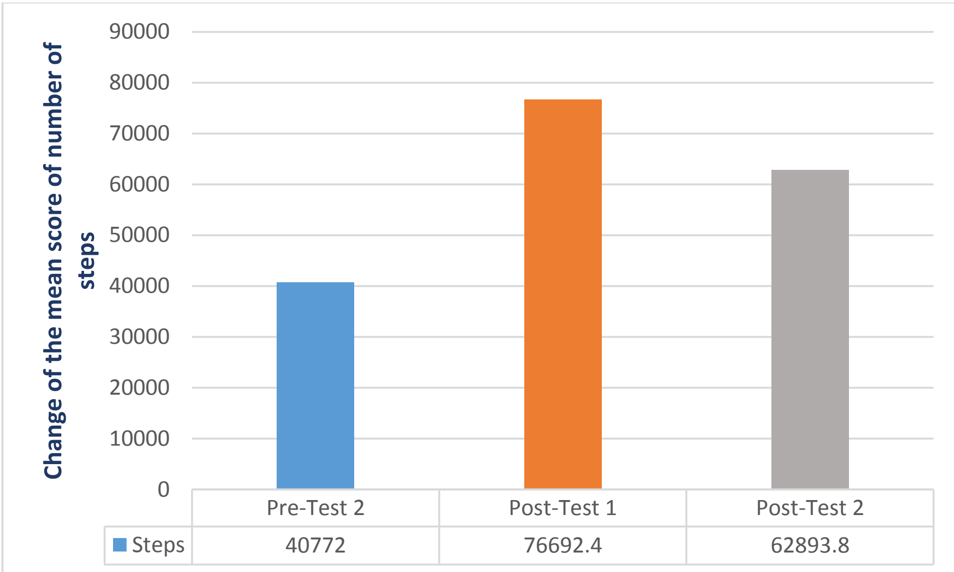


Figure 51. Change of number of steps mean score prior to and after training

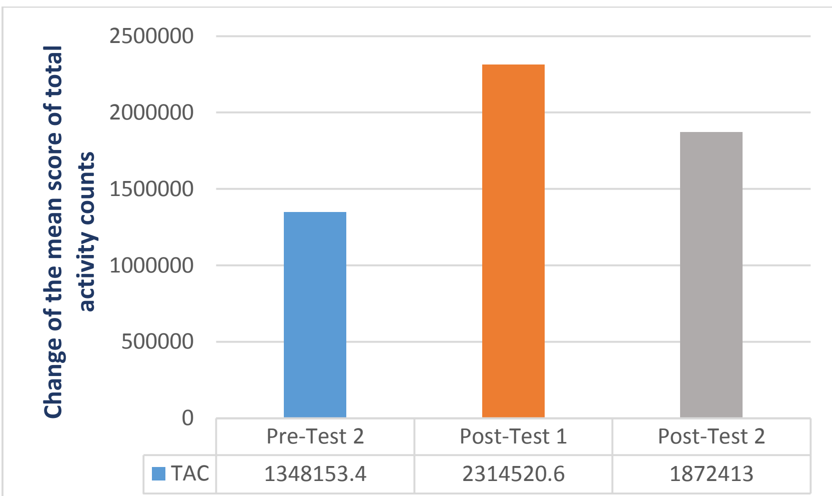


Figure 52. Change of total activity counts mean score prior to and after training

3. Participation Level

In addition to the accelerometer data presented earlier, which showed improvement in the participants' participation level, we used LIFE-H questionnaire to capture changes in overall quality of life, including changes in communication, community life, education, employment, fitness, housing, interpersonal relationships, mobility, nutrition, personal care, recreation, and responsibilities. The results revealed that, there were no significant differences found between pretest one and two.

Communication. There was non-significant improvement in the mean score of communication from 8.99 ± 1.08 to 9.52 ± .69 (6% improvement) (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of 1.52 (Noreau et al., 2004). A repeated measures ANOVA did not reveal a statistically significant difference between baseline and 1 month follow up ($F(1, 4) = 3.39$, $p = .139$) (Table 63 & Figure 53).

Community life. There was non-significant improvement in the mean score of community life, from 4.66 ± 5.05 to 6 ± 5.47 (20% improvement) (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of 2.17 (Noreau et al., 2004). A repeated measures ANOVA did not reveal a statistically significant difference between baseline and 1 month follow up ($F(1, 4) = .151$, $p = .717$) (Table 63 & Figure 53).

Education. There was non-significant improvement in the mean score of education, from 7.53 ± 1.18 to 8.55 ± 1.37, a 14% improvement (Table 63). A repeated measures ANOVA showed no statistically significant difference between baseline and 1 month follow up ($F(1, 4) = 5.07$, $p = .087$) (Table 63 & Figure 53).

Employment. There was non-significant improvement in the mean score of employment, from 2 ± 4.47 to 4 ± 5.47 (0% improvement) (Table 63). There was a non-significant difference between baseline and 1 month follow up, as indicated by the repeated measures ANOVA ($F(1, 4) = 1$, $p = .374$) (Table 63 & Figure 53).

Fitness. There was non-significant improvement in the mean fitness score, from 8.27 ± 1.18 to 9.10 ± .66 (12% improvement) (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of

3.71 (Noreau et al., 2004). A repeated measures ANOVA did not reveal a statistically significant difference between baseline and 1 month follow up ($F(1, 4) = 3.22$, $p = .147$) (Table 63 & Figure 53).

Housing. There was non-significant improvement in the mean housing score, from 8.10 ± 1.98 to 9.15 ± .89 (18% improvement) (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of 1.56 (Noreau et al., 2004). According to a repeated measures ANOVA, there was not a statistically significant difference between baseline and 1 month follow up ($F(1, 4) = 2.22$, $p = .210$) (Table 63 & Figure 53).

Interpersonal relationships. There was non-significant improvement in the mean interpersonal relationships score, from 9.91 ± .20 to 10 ± .00 (1% improvement) (Table 63). A repeated measures ANOVA did not reveal a statistically significant difference between baseline and 1 month follow up ($F(1, 4) = 1$, $p = .374$) (Table 63 & Figure 53).

Mobility. There was non-significant improvement in the mean mobility score, from 7.65 ± 1.20 to 9 ± 2.23 (18% improvement) (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of 2.85 (Noreau et al., 2004). A repeated measures ANOVA did not reveal a statistically significant difference between baseline and 1 month follow up ($F(1, 4) = 2.27$, $p = .206$) (Table 63 & Figure 53).

Nutrition. The results showed non-significant improvement in the mean nutrition score, which did not indicate meaningful change over time when compared to the minimum detectable change score of 1.93 (Noreau et al., 2004). There was no statistically significant difference between baseline and 1 month follow up, based on a repeated measures ANOVA (F(1, 4) = .000, p = .999) (Table 63 & Figure 53).

Personal care. There was non-significant improvement in the mean personal care score, from 7.37 ± 1.85 to 8.60 ± .80, a 22% improvement (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of 1.30 (Noreau et al., 2004). A repeated measures ANOVA did not reveal a statistically significant difference between baseline and 1 month follow up (F(1, 4) = 3.34, p = .141) (Table 63 & Figure 53).

Recreation. There was non-significant improvement in the mean recreation score, from 8.40 ± 1.26 to 9.10 ± 1.01 (9% improvement) (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of 5.95 (Noreau et al., 2004). Based on a repeated measures ANOVA, there is not a statistically significant difference between baseline and 1 month follow up (F(1, 4) = 3.86, p = .121) (Table 63 & Figure 53).

Responsibilities. There was non-significant improvement in the mean responsibilities score, from 8.27 ± 2.02 to 9.15 ± 1.05 (15% improvement) (Table 63), which did not indicate meaningful change over time when compared to the minimum detectable change score of 1.10 (Noreau et al., 2004). A repeated measures ANOVA did not reveal a statistically significant difference between baseline and 1 month follow up (F(1, 4) = 1.85, p = .245) (Table 63 & Figure 53).

Total score of LIFE-H. The results showed significant improvement in the mean total score of LIFE-H, from 8.480 ± .89 to 9.10 ± .64 (8% improvement) (Table 63), which indicated meaningful change over time when compared to the minimum detectable change score of 0.68 (Noreau et al., 2004). A repeated measures ANOVA revealed a statistically significant difference between baseline and 1 month follow up ($F(1, 4) = 14$, $p = .020$) (Table 63 & Figure 53). The greatest changes were seen in the personal care (22%), community life (20%), mobility (18%) and housing (18%) categories (Table 63). These results were supported by the accelerometer data. Table 63 shows the summary of the ES statistics for each life domains.

Table 63. Mean ± SD LIFE-H categories changes prior to and after training

	Baseline	**Follow up**	**Percentage Change (between baseline and follow up)**	**F**	**df**	**p-value**	**ES**
Communication	8.99± 1.08	9.52± .69	5.89%	3.39	1,4	.139	.82 ^{L}
Community life	4.66± 5.05	6 ± 5.47	28.75%	.151	1,4	.717	.2 ^{S}
Education	7.53±1.18	8.55±1.37	13.54%	5.07	1,4	.087	1 ^{L}
Employment	2±4.47	4± 5.47	100%	1	1,4	.374	.45 ^{S}
Fitness	8.27± 1.18	9.10± .66	10%	3.22	1,4	.147	.80 ^{L}
Housing	8.10±1.98	9.15± .89	12.96%	2.22	1,4	.210	.7 ^{L}
Interpersonal relationships	9.91±.20	10± .000	0.90%	1	1,4	.374	-.11 ^{S}
Mobility	7.65± 1.20	9 ± 2.23	17.64%	2.27	1,4	.206	.7 ^{L}
Nutrition	8.55± 2.06	8.55± 2.10	0.02%	.000	1,4	.999	-2.95 ^{L}
Personal care	7.37 ± 1.85	8.60 ± .80	16.68%	3.34	1,4	.141	.8 ^{L}
Recreation	8.40 ± 1.26	9.10 ± 1.01	8.33%	3.86	1,4	.121	.87 ^{L}
Responsibilities	8.27±2.02	9.15± 1.05	10.64%	1.85	1,4	.245	.60 ^{L}
Total score	8.48± .89	9.10± .64	7.31%	14	1,4	.020*	1.6 ^{L}

*. Significant difference pre to post ($p<.05$).
^{L} ES of .80 or more =large effect
^{M} ES of .50 = moderate effect
^{S} ES of .20 = small effect

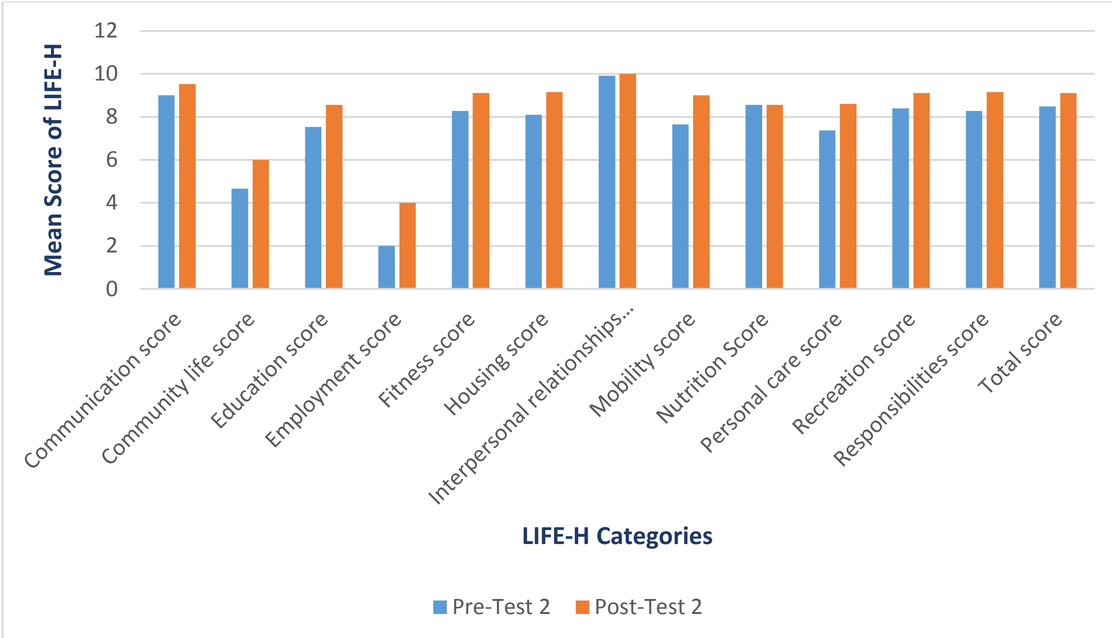


Figure 53. Change of LIFE-H mean score prior to and after training

Adverse Events

No adverse events occurred during the study except for very mild fatigue following the training, which disappeared once participants returned home.

CHAPTER V. DISCUSSION

In the last decade, robotic training has been emphasized in the literature as a new and promising therapy for individuals with neurological conditions. Numerous studies documents the effectiveness of upper and lower robotic therapy; however, the efficacy of robot-assisted, task-specific ankle training on children with CP is not well established (Aharonsona & Krebs, 2012; Fasoli et al., 2008; Fluet et al., 2010; Frascarelli et al., 2009; Krebs et al., 2009; Patritti et al., 2010; Borggraefe et al., 2010; Meyer-Heim et al., 2009; Smania et al., 2011). The primary focus of this pilot study was to advance our understanding of the influence of robot-assisted, task-specific ankle training (anklebot) in improving deficits across the three domains of the ICF (Body Function and Structures, activity, and participation) in children with CP. This is the first study of its kind to examine the influence of anklebot in improving deficits across the three domains of the ICF in children with CP. This chapter summarizes the study findings, applies results to the current literature, interprets conclusions, and discusses study limitations and implications for practice and research.

Aims and Findings

We hypothesized that robot-assisted, task-specific ankle training would improve Body Function and Structures including: strength, tone, muscle architecture, ROM, ankle control and performance, and balance in children with CP. We also hypothesized that enhancements in Body Function and Structures impairments would improve activity, including gait. Changes at the activity would also potentially influence the subjects' participation level. Data from two pre-tests and two post-tests were collected and analyzed to show the impact of this new robotic intervention on the different parameters assessed under the three domains of the ICF. The two pre-tests were used to establish the influence of maturation and any other therapies subjects received prior to the intervention, while the two post-tests reflect the training and learning (plasticity) effect of the robot-assisted ankle intervention. The results showed no changes in pre-testing numbers for any of the outcome measures, indicating the children were not experiencing noteworthy improvement from usual physical therapy (concurrent care) prior to this intervention. Therefore, we can attribute the significant betterment in the post-tests to our intervention. Table 64 summarize the significant study findings.

Table 64. Significant study's findings organized by ICF domain and affected side

ICF Domains		**Significant Result**	
1. Body Function and Structures		**Less-affected side**	**More-affected side**
	Strength	**Ankle:** DF, PF, inversion & eversion **Knee:** flexion **Hip:** adduction & flexion	**Ankle:** DF, PF, inversion, eversion **Knee:** flexion **Hip:** adduction, flexion, abduction & extension
	Spasticity	Hamstring	Gastrocnemius
	ROM	**Ankle:** DF (active & passive), PF (active & passive), inversion (active & passive) & eversion (active & passive)	**Ankle:** DF (active & passive), PF (active & passive), inversion (active & passive) & eversion (active & passive) **Knee:** flexion (active)
	Muscle architecture	TA CSA	
	Ankle control	Ankle control	Ankle control
	Ankle performance	Ankle accuracy Ankle smoothness	Ankle accuracy Ankle smoothness
	Balance	PBS	
3. Participation	**LIFE-H**	Total score	

Note: Activity was not included because it was not significant

Figure 54 illustrates the many potential impairments of the Body Function and Structures domain that limits activity including walking that children with CP may experience. In turn, these musculoskeletal impairments and activity limitations restrict the children's ability to participate and engage in different societal roles including leisure activities and education, which can lead to further restrictions in work and family life. It can result in an ongoing cycle of change where the degradation of one element can negatively influence other elements within the domain and between domains. In contrast, positive influence on one or more elements may result in significant improvements within and between domains.

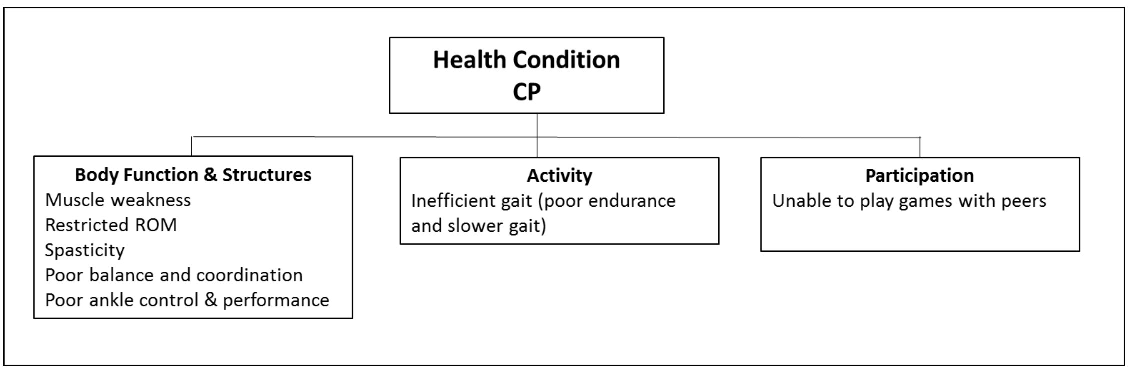


Figure 54. Deficits across the three domains of ICF (WHO, 2002)

1. Body Function and Structures Level Changes

In general, since our training targeted this level, participants showed improvement in most Body Function and Structures outcome measures.

Strength. Children with CP present with lower limb weakness, especially distally, which is considered the main limiting factor in walking efficiently (Dodd, Taylor, & Graham, 2003; MacPhail & Kramer, 1995; Ross, Engsberg, & Collins, 2006; Wiley & Damiano, 1998). It is important to note that muscle weakness outweighs spasticity in causing the greatest limitations in motor skills in children with CP (Ross & Engsberg, 2007). Weakness is most noticeable in ankle plantar flexors and dorsiflexors, followed by the hip abductors and extensors and knee flexors (Damiano, Vaughan, & Abel, 1995; Eek & Beckung, 2008; Engsberg, Ross, Olree, & Park, 2000; Ross & Engsberg, 2007; Wiley & Damiano, 1998). Children with CP suffer from weaker dorsiflexors and plantarflexors by as much as 30%–35% when compared to children without disability, leading to inadequate power production during walking (Cioi et al., 2011; Eek, Tranberg, & Beckung, 2011). Improving the strength of the lower limbs automatically improves motor function and gait as well as participation in leisure and social events (Damiano & Abel, 1998; Damiano, Martellotta, Sullivan, Granata, & Abel, 2000; Kramer & MacPhail, 1994; McBurney, Taylor, Dodd, & Graham, 2003; Ross & Engsberg, 2007).

Our results showed that actively training participants with robot-assisted ankle training using high intensity (528 repetitive motions for each ankle per session for 12 sessions) and high specificity (accuracy of motion to displayed targets) led to significant gains in muscle strength for all five subjects in numerous areas: bilateral ankle dorsiflexors, evertors, invertors, plantarflexors, knee flexor, hip adductor, hip flexor, (MA) hip abductor, and (MA) hip extensor. Our findings are consistent with past studies (Bütefisch, Hummelsheim, Denzler, & Mauritz, 1995; Lum et al., 2002; Riener, Nef, & Colombo, 2005). There was no consensus in the literature regarding the dose of training, which ranges from 20–60 minutes of two to five times per week for a period ranging from 2–12 weeks with a total of approximately 560–640 repetitions per session (Boian et al., 2002; Burdea et al., 2013; Forrester, Roy, Krebs, & Macko, 2011; Forrester et al., 2013; Jung, Diaz, & Macko, 2014; Krebs et al., 2011; Macko, 2011; Kwakkel, Kollen, & Krebs, 2008; Swinnen et al., 2014). Although, the participants in our study performed less than this recommended amount (528 repetitions per ankle per session twice a week for 6 weeks), it result in strength changes.

The children sustained their strength gains at follow-up, which may have been due to the increase in daily activity following training. Posttest and follow up data from the accelerometer and parents' report (LIFE-H scores) indicated increases in overall child activity that likely influenced the maintenance of strength gains seen at the end of the study. Because we trained both legs, the participants experienced bilateral improvement, but the improvement was more evident in the more-affected side. Training both legs was important since one of our desired outcomes was to enhance motor capacity in walking, which is a bilateral task, it would be inappropriate to train one side only and expect improved gait outcomes. Additionally, Allen et al. (2000) reported that children with hemiplegic CP have abnormalities in ankle kinematics in the less affected limb as well as the more affected limb due to their endeavors to achieve a more symmetric gait pattern. This makes sense when considering that unilateral motor impairment in children occurs most often during significant stages of motor development resulting in abnormal motor coordination bilaterally (Allen et al., 2000). Adequate strength is critical for normal motor control of gait. The timing and sequencing require a balance in motor activity that without effective strength will result in other muscles compensating for the weakness (Brunner & Rutz, 2013; Gage, Schwartz, & Koop, 2009; Inman, Ralston & Todd, 1981; Perry & Burnfield, 1993).

Activating the correct muscles during the gait cycle enhances walking ability and efficiency, which in turn could lead to improve participation level (Brunner & Rutz, 2013). Improvement in walking ability was evident by the data from the gait mat analysis, which showed a more efficient gait pattern following the training. Further explanation regarding the impact of strength on gait will be discussed later in the gait section. Additionally, children with strong muscles usually have stronger ligaments and tendons, leading to less tendency to fall and better balance (Horlings, Van Engelen, Allum, & Bloem, 2008).

Spasticity. One of the most common problems among children with CP is spasticity, which affects joint function and can lead to movement restriction (Flett, 2003). In our participants, spasticity was noted in the gastrocnemius, which overpowered the tibialis anterior (causing equinus) and in the hamstring influencing the quadriceps (hip and knee flexion) (Rodda, Graham, Carson, Galea, & Wolfe, 2004). This imbalance between the weak antagonists and the spastic agonists can lead to deficits in strength and ROM resulting in standing posture instability and ambulation restriction (Damiano & Abel, 1998; Shepherd, 1980; Zarrugh & Radcliffe, 1978). Increasing volitional motor control and strength in the antagonist may help to reduce spasticity in the agonist and improve motor function and gait (Fasano, Broggi, Barolat-Romana, & Sguazzi, 1978; Østensjø, Carlberg, & Vøllestad, 2004; Tuzson, Granata, & Abel, 2003).

The findings of this study showed reductions in the spasticity of the bilateral gastrocnemius at 1 week post-training, and these reductions were even greater at 1 month follow up. The same results were also seen with the hamstrings; where spasticity declined at 1 week post-training and continued to decline at 1 month follow up. These results were significant for the more-affected gastrocnemius ($p = .043$) and less-affected hamstring ($p = .005$). The less-affected gastrocnemius ($p = .055$) and more-affected hamstring ($p = .058$) trended toward significance; however, due to the small sample size ($n = 5$), they did not meet the requirements for significance. The children in our sample mostly came with higher spasticity in the right gastrocnemius and hamstring; regardless of statistical significance, the greater changes were seen in the more-affected side likely due to greater involvement and greater chance for improvement. More-affected gastrocnemius spasticity dropped 15.2 degrees (showing 72% improvement), while less-affected gastrocnemius spasticity dropped 11.2 degrees (showing 60% change) at the 1-month follow-up comparing to baseline. Also, the more-affected hamstring dropped 18.8 degrees (showing 55% improvement), while the less-affected hamstring dropped 10.6 degrees (showing 42% improvement) at the 1-month follow-up. The reduction in spasticity was complemented by gains in muscle strength of both the TA and quadriceps for all five children enhancing their motor control and functional capacity. This was evident by the data from the Boyd and Graham, gait mat, accelerometer, and LIFE-H data. The results of our study showed significant improvement in antagonist strength bilaterally and more-affected quadriceps strength. This finding is in line with Lee et al.'s (2016) study that showed improved strength and decreased spasticity after 30 minutes of upper limb robotic training, followed by 30 minutes of conventional training, 5 days per week for 2 weeks. Although Lee et al. used upper limb robotics, the concept of skilled, highly repetitive training remained the same as in our training. Increased tibialis anterior strength has been shown to improve dorsal torque of the ankle joint, thus reducing equinus and improving ankle joint mobility (Park & Kim, 2014). This is important because if the muscle can stretch, it gains the ability to grow with the surrounding bone and increases the child's flexibility, which can potentially decrease the possibility of deformity (NHS Choices, 2017).

The improvements in muscle tone were observed on both legs but were greater on the more-affected side. The participants' parents' opinions supported these results, "My children's ankles have become more flexible and less dependent on their ankle foot orthosis (AFO) compared to pre-training." The decline in muscle tone could benefit motor skill development such as walking, as evidenced by the improvement seen in the gait mechanics. Our findings of muscle tone reduction following 6 weeks of robotic training have similarities to the findings in previous literature (Hesse et al., 2003; Mirbagheri et al., 2011; Roy, Forrester, Macko, & Krebs, 2013; Selles et al., 2005; Wu et al., 2011; Zhang et al., 2002) that used similar training programs with individuals with a variety of physical disabilities.

Muscle architecture. Children with CP presented with smaller muscle size compared to their typical peers (Barber et al., 2011). Literature emphasized the importance of muscle size as it relates to force generation and forward propulsion influencing balance during locomotion (Barber & Boyd, 2016). The literature also revealed a strong correlation between decreased muscle mass and increased risk of disability (Janssen et al., 2004).

Diagnostic ultrasound was used to capture muscle architecture parameters, including cross sectional area (CSA) and muscle thickness (MT), and the pennate angle (PA) for the bilateral AT, TA, and gastrocnemius muscles. The ultrasound imaging revealed a change of bilateral CSA of medial gastrocnemius and TA as well as TA thickness and more-affected AT CSA as a result of the gain in muscle strength and coordination (Aagaard et al., 2001; Kawakami, Abe, Kuno, & Fukunaga, 1995; Mcnee, Gough, Morrissey, & Shortland, 2009; Riad, Modlesky, Gutierrez-Farewik, & Broström, 2012; Toner, Cook, & Elder, 1998; Wu et al., 2011). Unfortunately, these changes were not significant (except in the less-affected tibialis anterior CSA), which might be due to the small sample size (n = 5). The significant result in TA CSA could be explained by the strength results, which showed that, across different muscles, the TA was experiencing greater a gain in strength at follow up compared to baseline. The majority of our subjects used an AFO, which supported the weak TA but also restricted its motion, leading to further weakness (Lairamore, Garrison, Bandy, & Zabel, 2011). By training this muscle with high-frequency training, the participants were able to gain selective activation of the TA, hence strengthen the muscle, and became less dependent on the AFO. This was evident with one participant who was able to switch to a less restrictive bracing system toward the end of the program. The participant was using a supra malleolar orthotic (SMO), then switched to a less restrictive UCB shoe insert. By moving to a less restrictive orthotic system, the participant was able to promote her ability to maintain and improve upon range, strength, and function gained by the Anklebot. The remaining participants decreased the amount of time they wore their orthosis, and with a more intense dose, perhaps they could move to a less restricted AFO or totally cease using the orthotics.

We attributed the changes in muscle architecture parameters seen in this study to the changes seen in muscle strength. The literature showed that strength training stimulates enlargement of the cell due to synthesis of more myofilaments (Haff & Triplett, 2015). This is consistent with the results of several studies showing that muscle structure and size are strongly associated with strength (Enoka, 2002; Lieber & Friden, 2000; Pitcher, 2012). The CSA and thickness are also positively correlated with force production (Bloomquist et al., 2013; Rosenberger et al., 2017).The greater and thicker the fiber, the more force it can generate. Even though the robot does not produce any resistance to movement, the child's activity resulted in force production and strengthening that was correlated to changes in muscle architecture.

Additionally, the results of this study showed the CSA of gastrocnemius muscles in the more affected leg was smaller than that of the less affected leg at follow up. This was due to the abnormal compensation pattern on the less affected side, which effects the proximal joints more than the distal and results in ankle kinematics close to the normal range, hence the difference from the more affected side (Cimolin, Galli, Tenore, Albertini, & Crivellini, 2007). On the other hand, the results showed that the CSA of the AT and TA in the more affected leg is larger than that of the less affected leg, which is contrary to what has been mentioned in the literature. The explanation for the greater size of the more-affected muscles comparing to the less-affected might be greater improvement in that side, which was evident from the data from the HHD. The correlation between CSA and the maximum force produced by the muscle explains why the more involved leg produces less power than the less affected one (Elder et al., 2003). The smaller the CSA, the less force produced, which was evident in our data from the HHD. This is in line with existing evidence showing that the muscle size of the ankle dorsiflexors (Bandholm, Magnusson, Jensen, & Sonne-Holm, 2009) and plantarflexors (Elder et al., 2003; Mohagheghi et al., 2007) is smaller in the impaired limbs of children with hemiplegic CP. On the other hand, a decline on the bilateral Achilles tendon CSA existed, although muscle volume slightly improved due to training. However, this did not show a decline in participants' conditions. On the contrary, the literature showed that tendon CSA is not associated with muscle volume, and it does not increase with training (Fukutani & Kurihara, 2015; Hansen, Aagaard, Kjaer, Larsson, & Magnusson, 2003; Reeves, Maganaris, & Narici, 2003). Furthermore, the force production comes from the muscle fiber and not the tendon, and this makes the tendon's size less important compared to the muscles.

The literature showed that pennation angle could change in response to physical inactivity or training such as strengthening practice (Aagaard et al., 2001). This finding is in line with our results, which showed non-significant changes in PA of the bilateral gastrocnemius. The change in PA might relate to the change in CSA, which would be supported by the literature that showed increases in quadriceps CSA were related to the increase in muscle volume, which had a positive relationship with PA (Aagaard et al., 2001). As high repetitive training impacts muscle strength and architecture, it leads to improvement in gait velocity and increased walking efficiency (Bland et al., 2011) as seen in our study. Literature showed that larger thickness was associated with greater dorsiflexion during normal walking in the swing phase (Bland, Prosser, Bellini, Alter, & Damiano, 2011). Bland et al. (2011) further found that a larger pennate angle was associated with greater dorsiflexion at initial foot contact. They also noted that a larger CSA was associated with greater dorsiflexion in the swing phase and greater dorsiflexion at toe-off (Bland et al., 2011). Overall, the literature supports a correlation of improved motor capacity and increased PA. Although the data in this study for PA was not significant, the changes were similar to what has been previously reported in the literature during improved motor performance. The lack of change might related to the training dose being low.

Range of motion. Children with CP suffer from restricted ROM, resulting in impaired function and ability to perform daily activities (Wichers, Hilberink, Roebroeck, van Nieuwenhuizen, & Stam, 2009). Muscle tightness leads to shortening in muscle-tendon length, which can restrict ROM and create muscle imbalance (Page, 2012; Willerslev-Olsen, Lorentzen, Sinkjær, & Nielsen, 2013). The literature supports the correlation between ROM and the level of spasticity in children with CP (Hägglund & Wagner, 2011). This was shown by our pre-testing data, which indicated that our participants experienced increased muscle tone leading to restriction in lower-limb ROM. Our training program targeted the ankle joints with high repetitive movement, resulting in improvement in weaker antagonists. Our program also reduced spasticity in the agonists, which allowed the child to move his/her ankle through its full ROM, thus improving joint flexibility and allowing the joints to move more freely throughout the range (Hesse et al., 2003). The literature support the idea by increasing volitional activity that will lead to decreases in abnormal tone hence, increase ROM (Nagayama, 2014).

Changes in lower-limb ROM showed significant improvements in the active and passive ROM of the ankle bilaterally in addition to more affected active knee flexion which was consistence with previous research (Beretta et al., 2015; Deutsch et al., 2001b; Hägglund and Wagner, 2011; Selles et al., 2005; Wu et al., 2011; Zhang et al., 2002). All these studies support our findings of ROM gains bilaterally, especially at the ankle, following varying doses of robotic training. The improvement seen in ankle ROM, as measured by the goniometer, was in line with the observation of the progression of training setup. Across subjects, we initially started the robotic training setup with 25% of the available range of training where subjects moved through a very short range due to the restriction on the ankle. We then progressed at the middle of the training to 50% of available range, and finally progressed to 100% by the end of training, where subjects moved through full range of training setup.

Improvement in ROM combined with adequate strength allows children to move freely and smoothly without stiffness or pain. Additionally, increased dorsiflexion ROM led to better leg positioning for more effective production and absorption of power during walking as seen by the improvement in gait parameters following training.

Ankle control and coordination. Evidence showed distal selective motor control is more impaired than proximal selective motor control in the lower extremities in patients with spastic cerebral palsy (Fowler, Staudt, & Greenberg, 2010; Ross & Engsberg, 2002), and the most affected joint is the ankle (Bland et al., 2011). Therefore, targeting the distal joint with focus training was thought to have a positive effect on many joints in the lower extremities. Children with CP suffer from poor selective voluntary dorsiflexion muscle control, which results in dragging their toes during walking; this leads to walking with an inefficient gait and at high risk of falling (Fowler & Goldberg, 2009; Rodda, Graham, Carson, Galea, & Wolfe, 2004; Sung & Bang, 2000). Additionally, hemiplegic ankle may cause asymmetric joint kinetics and kinematics (Carlsöö, Dahlöf, & Holm, 1974; Chen, Patten, Kothari, & Zajac, 2005; Olney & Richards, 1996; Perry & Davids, 1992) and poor muscle coordination during mobility (Den Otter, Geurts, Mulder, & Duysens, 2007; Higginson et al., 2006). Strengthening the muscle decreases the spasticity, thus allowing for more flexibility to move throughout the ROM actively and building toward a coordinated, controlled movement, as we saw over the course of the study. The results of this study document significant improvements in bilateral ankle control ($p = .016$, $p =$

.004). When our participants were asked to selectively dorsiflex their ankles at baseline testing (pre-test 2), they could not comply, due to the weakness of the TA and spasticity of the gastrocnemius. Instead, they substituted movement of the toe extensors (extensor hallucis longus and extensor digitorum longus) or knee and hip flexion. This was evident by a baseline score of 2 (indicating dorsiflexion achieved mainly by toe extensor with some TA) for more-affected ankle control and 3 (indicating dorsiflexion achieved by TA with hip and knee flexion) for less-affected ankle control. At the 1-month follow-up, the score for more-affected ankle control improved to 3 (indicating dorsiflexion achieved by TA but with knee and hip flexion). The score for less-affected ankle control improved to 4 (indicating the ability to activate TA to achieve dorsiflexion without any muscle substitution).

High repetition of our training over a 6-week period helped the children in our study to isolate movements and decrease the amount of muscle substitution by building up ankle strength and control in addition to sensory and motor memory of the trained movements. These findings are consistent with those of Cioi et al. (2011). More evidence was presented in a study by Wu et al. (2011), where significant improvement was found in selective motor control ($p = .005$) following 6 weeks of portable rehabilitation robot training in children with CP. Similarly, Forrester et al. (2011) documented improvement of paretic ankle motor control after 6 weeks of robotic feedback training in chronic stroke subjects. Furthermore, our results are in line with findings by McGehrin et al. (2012), who reported improvements in ankle control in the form of increased smoothness, accuracy, and speed after a single session of ankle robot training in a sub-acute stroke population.

In summary, strength, tone, ROM, and coordination work together to create efficient movement patterns across each joint. When strength is improved, the tone will drop, which helps muscle to move through the full range without restriction. This then builds up more control and coordinated movement at the joint. Restriction or dysfunction at any joint in a closed chain environment affects how each joint works and how other joints (above and below) function as well. For instance, a restriction in the ankle joint could lead to immobility (contracture) at the ankle, leading to knee instability, which may then result in hip dysfunction. Understanding how all these elements work together through different joints to execute certain movements is vital. Such understanding can help us choose the most efficient intervention to help these kids be independent in the most sufficient way.

Ankle performance. During the first few weeks of training, the participants' performance during sessions was jerky and irregular; participants made fewer successful attempts throughout the different games played. As they got closer to the last training session (session #12), the children were better able to perform more successful, faster, and smoother movements on the robot. This is evident by the significant increase of the accuracy of bilateral (LA/MA) ankle movement by 58% and 54%, respectively, and by the increase in smoothness of bilateral (LA/MA) ankle movements by 17% and 16%, respectively. In addition to the objective data recorded by the robot that showed bilateral improvements in ankle performance, the researcher's subjective observation revealed that as the children mastered the games, the session times decreased; as they improved their ankle control, they needed less assistance from the therapist to play the games. Furthermore, reduction of hamstring and gastrocnemius spasticity as well as increased

ROM of the ankle allowed the children to move their ankles in a more controlled smooth manner as shown by the robotic intrinsic evaluation. These popup evaluation screens not only showed us the participants' performance but also helped us adjust our training accordingly. Once participants achieved good accuracy and smoothness scores, we challenged them by increasing the difficulty of the games. This unbiased objective feedback from the robot helped participants to regulate and self-correct their own movements during each session. The intermittent feedback has been shown to be superior to continuous feedback in promoting motor learning (Emmert et al., 2017; Johnson et al., 2012). Our findings of increase ankle performance were consistent with two studies by Deutsch et al. (2001a, 2001b) that found ankle robotic training (Rutgers Ankle haptic interface) improved coordination and task accuracy by up to 100% for children with musculoskeletal injuries and 45% for adults with stroke. Improvements in ankle performance following robotic training in adults with strokes and children with CP have been documented in several research studies (Burdea et al., 2013; Deutsch, Lewis, and Burdea, 2007; Forrester, Roy, Krebs, & Macko, 2011; McGehrin et al., 2012; Roy, Forrester & Macko, 2011).

Balance. Balance is crucial to maintain the stability required for all movements, including walking (Woollacott & Shumway-Cook, 2005). Postural instability and poor balance are disabling for children with CP because their ability to recover from stability threats in their surroundings is limited, leading to an increased risk of falling (Woollacott & Shumway-Cook, 2005). Several factors contribute to poor balance in children with CP, including spasticity and contractures, reduced ROM (Shumway-Cook, Hutchinson, Kartin, Price, & Woollacott, 2003), muscle weakness (Horlings, Van Engelen, Allum, &

Bloem, 2008), impaired muscle-action sequence (Shumway-Cook, Hutchinson, Kartin, Price & Woollacott, 2003; Woollacott & Shumway-Cook, 2005), poor ankle-eye coordination, and poor ankle control. Robot-assisted ankle training focused on improving the majority of these published factors related to poor balance performance. Balance is a fundamental component to many activities; improvement in balance will extend to other activities, including walking with more efficient gait (Bohannon, 1989).

The results of this study indicate a significant improvement in balance score for all participants, with greater improvement for the more involved child (level III GMFCS). In general, improvements in PBS scores were higher than the MDC of 1.59 and MCID score of 5.83 (Chen et al., 2012). The fifth subject, who had two points change, was the only exception. This result is consistent with research by Picelli et al. (2012), who compared the ability to improve balance using robot-assisted gait training in patients with Parkinson's disease against traditional therapy. They found that 12 sessions (40 minutes, three days per week, for three weeks) of robotic training caused gains in patients' Berg Balance Scale and Nutt's ratings (Berg: 43.44 ± 2.73; Nutt: 1.38 ± 0.50) compared to traditional training (Berg: 37.27 ± 5.68; Nutt: 2.07 ± 0.59). This improvement was sustained at the one month follow-up. Several other researchers have reported similar results with post-stroke and CP patients (Deutsch, Latonio, Burdea, & Boian, 2001a; Deutsch, Latonio, Burdea, & Boian, 2001a b; Wu, Hwang, Ren, Gaebler-Spira, & Zhang, 2011; Freivogel, Mehrholz, Husak-Sotomayor, & Schmalohr, 2008). This study, however, showed improvement to a complex impairment following ankle motor coordination training in children with CP.

Balance improvement can be attributed to the improvement seen in tone, ROM, strength, ankle-eye coordination, endurance, and ankle control. Our participants present at baseline with tip-toe walking due to spasticity, which led to decreased heel strike during the stance phase, thus impairing ankle movement necessary for standing balance (Burtner, Woollacott, Craft, & Roncesvalles, 2007). As such, the results of this study showed reduction in muscle tone at the ankle, which led to smoother dynamic body movement and better balance.

The results also showed improvement in ROM, which led to more flexibility within the joints and thus more controlled mobility in standing and walking. This is consistent with several studies (Spink et al., 2011; Nakamura et al, 2011; Wuebbenhorst & Zschorlich, 2011).

The results of the study also revealed gains in muscle strength, which contributed to improved muscle control to allow for better movement and a decrease in abnormal postural support. Improved balance reduces the risk of fall and can increase movement confidence (Horlings, Van Engelen, Allum & Bloem, 2008) which was reported by the parents. The results also showed gains in hip muscle strength, resulting in better stability and the ability to balance on one leg, which is important for several daily tasks, including dressing, walking on uneven surfaces, and stairs (Eek & Beckung, 2008). This was evident by the increase in single support time following training. Furthermore, ankle muscle weakness impairs the muscle response sequences wherein the hamstring/quadricep muscles are activated before the gastrocnemius/tibialis anterior, leading to poor balance (Shumway-Cook, Hutchinson, Kartin, Price, & Woollacott, 2003;

Woollacott & Shumway-Cook, 2005). Therefore, improving ankle strength will lead to more distal to proximal muscle response sequences and better balance in standing.

Additionally, the results showed improvement in the children's ability to process and analyze visual information to control and guide the ankles while walking, leading to better balance. This is evident in the improvement of ankle performance (accuracy and smoothness) recorded by the robot. Furthermore, the findings of this study showed improvement in ankle control, which impacts the length of time the child can maintain the balance.

Balance improvement allows children to move more efficiently and navigate different environments (e.g. an uneven playground), thus increasing their participation in sports and leisure activities. Being more efficiently active and involved in play activity allows children to develop the necessary self-regulation for different daily tasks as well as friendships and strong social networks. This could impact their self-esteem and their sense of importance and belonging in their community. Furthermore, improvement in balance enhances the child's ability to control their body movement while performing different tasks, which limits excessive energy expenditure and reduces fatigue. Additionally, improving balance helps children appropriately adjust their body in response to threats, which will reduce the risk of fall and injury, thus increasing their participation in play activity (Shumway-Cook et al., 2003). Gaining better balance will significantly decrease the recurrence of ankle and knee ligament injuries during daily and recreational activities (Hrysomallis, 2007), and it will allow children with CP to master physical activity at the same level as their peers which could encourage them to pursue team sports and prevent social isolation. It also enhances the child's ability to carry out self-care tasks, thus improving their independence. Having a good balance helps these children improve their fine motor skills by improving their base and core stability to support the efficient use of their upper limbs while standing or sitting (Seeger et al., 1984; McCleneghan et al., 1992).

2. Activity Level Changes

The literature showed that children with CP are less physically active and suffer from greater activity limitations compared to their peers (Maher, Williams, Olds, & Lane, 2007; Van Zelst, Miller, Russo, Murchland, & Crotty, 2006). Children with CP are only active 40.2% of the time compared to typically developing peers who are active 49.6% of the time (Bjornson, Belza, Kartin, Logsdon, & McLaughlin, 2007). Based on the neuroplasticity principle of "use it or lose it," if children do not move regularly and suffer from reduced activity levels, the functioning and brain mapping of these electrical signals is changed and diminished, decreasing the children's functional ability and independence (Kleim & Jones, 2008; Byl et al., 2003) as well as education and employment (Donkervoort et al., 2007). Additionally, lack of activity leads to osteoporosis (the loss of bone density) and puts these children at a higher risk of fracture (Henderson, White, & Eisman, 1998; The United Cerebral Palsy Research Foundation and Educational Foundation, 1999; Henderson et al., 2002). Activity impairments, including insufficient walking patterns, will worsen and deteriorate with age; 50% of individuals with CP will experience a decline in walking ability before their mid-thirties, and 10% will stop walking entirely (Jahnsen, Villien, Egeland, & Stanghelle, 2004). This emphasizes the importance of improving activity at a younger age to limit the impact of age-related changes on their physical impairments.

Gait mechanics. Children with CP present with inefficient gait patterns (Berger, Quintern, & Dietz, 1982; Buckon et al., 2001; Winters, Gage, & Hicks, 1987), including asymmetry between the unaffected and affected leg (Fonseca et al., 2004; Olney, Griffin, & McBride, 1994), slower gait patterns, and inefficient energy expenditure while walking compared to their normal developing peers (Abel & Damiano, 1996; Rose et al., 1990). A major aim of CP rehabilitation is augmenting the recovery of muscle function to improve walking ability and enhance participation in everyday activities (Gilbertson, 2016). Gage's (2004) study illustrated five key requirements for efficient gait: stability in the stance phase, foot clearance during the swing phase, pre-positioning of the foot during the terminal swing phase, sufficient step length, and use of less energy while walking. Prior to our intervention, participants lacked all these key requirements for efficient gait pattern. Nevertheless, after training domain 1, we were able to change several of these key gait variables. This result was evident by the transfer effect of training subjects from sitting to impact gait spatiotemporal parameters, including stepping characteristics, cadence, and velocity. Notably, our participants, who were mostly classified as level I GMFCS and walked at a high functional level, showed improvement, illustrating the possibility of this intervention benefiting high to medium functioning children with CP. Several factors could contribute to the improvements seen in the gait mechanics, including improvement in muscle strength, spasticity, coordination, ROM, ankle control, and balance (Andersson, Grooten, Hellsten, Kaping, & Mattsson, 2003). As a result, based on phases of recovery in rehab, a patient cannot progress to the functional recovery level before having adequate strength and ROM to perform the functional activities. Our intervention provided a new paradigm for treating strength/ROM (among others at this domain level), which resulted in improvements in these factors, leading to more freedom and progression to a better gait pattern.

The common gait pattern of children with CP is characterized by adduction, excessive ankle plantarflexion, knee and hip flexion resulting from primary weakness in ankle dorsiflexor, knee extensors, hip abductors, and extensors (Rodda & Graham, 2001). These characteristics highlight the three important muscles regarding gait: hip abductors, ankle plantar flexors, and dorsiflexors, which all demonstrated significant increase in strength at follow-up. Indeed, the literature showed that hip abductors are more related to function than any other lower extremity muscle group (Ross & Engsberg, 2007). The hip abductor group is crucial for loading response, and its weakness led to contralateral pelvic drop and excessive hip adduction during gait, as seen at baseline (Perry & Davids, 1992). However, following training, the more-affected leg showed a 24% increase in hip abduction strength, which led to better stabilization for effective push-off, resulting in more efficient and symmetrical gait pattern. Furthermore, the bilateral increase in dorsiflexor strength helped participants to selectively control the ankle dorsiflexors to pre-position the foot for heel strike during stance phase and clear the ground during the swing phase, minimizing the slapping gait pattern that was seen at baseline (Gage, 2004; Pierce et al., 2004). The bilateral gain in ankle plantar flexor strength impacts the gait pattern, as they account for 50% of the propulsive force in walking (Gage, 2004). Stronger plantar flexors helped to control the progression of the tibia over the foot during the stance phase (Rodda & Graham, 2001). As a result of the strength gains in lower limb muscles, the participants improved their motor control as seen by the Boyed and Graham scale, which helped patients to shift their power generation for forward propulsion from the hip to the ankle, resulting in less hip and knee compensatory movement during walking (Rose & McGill, 1998). Enhancing these gait characteristics has been shown to increase walking efficiency (Gage, 2004; Tugui & Antonescu, 2013). In fact, this finding was demonstrated in all five subjects in this study. Additionally, weakness of the ankle's dorsiflexor and quadriceps muscle (Demura, Demura, Uchiyama, & Sugiura, 2014; Matsuda et al., 2015), along with spasticity in the plantar flexor muscles, negatively impacts the step length as seen in the baseline data, resulting in increased energy expenditure while walking (Ballaz, Plamondon, & Lemay, 2010; Dallmeijer, Baker, Dodd, & Taylor, 2011). Mean step length and cadence improved at follow-up, and both became more typical as per reported data in normal step length and cadence in young children (Dini & David, 2009). Unfortunately, these results were not significant, which is likely attributable to the small sample size (n = 5) and the fact that we did not directly train gait. Despite the small sample, all subjects experienced positive gain in the step length and cadence except for the younger and more-involved child, who did not experience any change. The lack of change might be attributed to intensity and frequency of training. The results highlighted large to medium effect size for gait parameters, which support the idea that change is impactful and clinically noteworthy, even if it isn't statistically significant.

The literature showed that a more intense training of 18 sessions of ankle robotics with 560 repetitions imposed greater improvement in step length and cadence (Forrester, Roy, Krebs, & Macko, 2011). This corresponds with Cordo et al.'s (2009) study, which showed greater gains in stride length by 21% and cadence by 14% following a longer program of 6 months of ankle robotic training as compared to our 6 weeks of training.

Additionally, improving muscle strength and decreasing antagonistic spasticity can increase movement efficiency and decrease energy expenditure while walking, resulting in less fatigue and the ability to walk longer distances. This finding was reported by the parents who "saw decline in their children's fatigability throughout the day and ability to walk further distances following the training." Moreover, accelerometer data indicated greater overall numbers of steps and increased activity level, suggesting an increase in overall energy availability. While we did not directly measure efficiency, parent reports indicated children were walking with more efficiency during daily tasks. The improvement that we saw in gait aligns with Gage's (2004) findings for efficient gait, specifically stability in the stance phase, foot clearance during the swing phase, pre-positioning of the foot during the terminal swing phase, sufficient step length, and using less energy while walking.

Gait asymmetry was affected mainly by the amount of the spasticity in the gastrosoleus and hamstring (Hsu, Tang, & Jan, 2003) along with the weakness of antagonists (Damiano & Abel, 1998; Zarrugh & Radcliffe, 1978). Due to this imbalance, our participant's relied less on the paretic leg, which shortens the single support phase on the paretic leg (32%), prolonging the support phase on the less-affected leg (34%). Additionally, after robotic-assisted training, participants experienced a decline in muscle tone and gain in muscle strength that resulted in increased muscle coordination (Boyd & Graham) and the ability to support their body weight and rely on the paretic leg for a longer period, leading to better symmetry during gait and better control of dynamic balance (Forrester et al., 2013). Furthermore, the participants' single support values following training became closer to that of healthy children (40%). The results also showed the mean stance duration decreased to 61, while the mean swing duration increased to 38. Although the change in mean scores was not statistically significant (p = .370, p = .374), we found a medium effect size indicating clinical significant and a trend toward a symmetric gait that is more typical of developing peers (60/40) (Dini & David, 2009).

Furthermore, gait speed is primarily influenced by muscle weakness and restricted ROM of the affected limb (Hsu, Tang, & Jan, 2003); hence, improvement in muscle strength and ROM impacts the gait speed, which is consistent with several studies (Bohannon, 1986; Carda et al., 2009; Flansbjer, Downham, & Lexell, 2006; Engsberg, Ross, & Collins, 2006). Walking velocity was faster in all five participants after training, showing 6% improvement at the 1-month follow-up. The mean velocity was 99 cm/sec. following training, only 4cm/sec. slower than their typically developing peers. Deutsch et al. (2004) conducted a similar intensity of robotic program that targeted the ankle and found comparable improvement of 11% in velocity. Similar gains in velocity were also reported by several other studies using robotic interventions targeting lower extremity bilateral symmetric motion, while our study focused on individual ankle motion bilaterally (Beretta et al., 2015; Meyer-Heim et al., 2007; Patritti et al., 2010). In fact, our study is the first to illustrate the impact of distal motor activity training on symmetrical walking ability in children with neurological motor impairment. In comparison, Krishnan et al. (2013) reported 30% improvement in walking velocity following 12 sessions of reduced guidance gait robotic training, greater than what was reported by our study. Nevertheless, Krishnan et al.'s findings were expected since their program specifically targeted gait, which was different than our program that focused on the ankle. Not only does the structure of training greatly enhance change in velocity but the dosage does as well. Cordo et al. (2009) used more intensive robotic training for 6 months and demonstrated greater gains in velocity by 37%, significantly higher than what was reported by our study. This emphasizes the importance of frequency of the dose to augment our results, and a logical next step would entail research to investigate varying doses.

We have anecdotal evidence from parents of participants who indicated their children had become faster as well as more confident and coordinated while walking. For instance, these parents noted specifically that their children interacted and participated more with peers during recreational activities. The mother of the more-involved participant reported that “her child’s tendency to fall decreased following training, which gave him the confidence to play baseball.” Although this incident involved only one child, this report suggests the likelihood that the risk of falling was decreased after training as a result of improving the velocity and step length, which was also supported by the literature (Hausdorff, Rios, & Edelberg, 2001). In general, the improvement in walking ability likely contributed to increased daily activities, as evidenced by the improvement in activity count measured by the accelerometer and parent reports.

Activity increase. The accelerometer results showed the total EE and the EE spent on light moderate and vigorous activities increased at the 1-month follow-up. The greater value of improvement was in EE spent in light and moderate activity. This increase in EE might be due to children adopting a healthier and more active lifestyle as well as the time of the year. The post-testing data was collected in winter, when children engage more in light and moderate activity compared to the vigorous activity, which usually happens in the summer. Post-testing was also conducted during the school year, when children engage in more light and moderate school activity. Improvement in EE tremendously impacts the quality of life. Spending less energy when walking helps children walk faster and for longer distances with less fatigue, providing the ability to be more active and engage in different social activities, which is the ultimate goal of our therapy (Brehm et al., 2008; Maltais et al., 2001; Rimmer, 2001). Ideally, EE is supposed to decrease as a sign of improvement, but our participants became more involved in activities following training, which could explain the increase in EE. This is evident in the questionnaire data and the increase in step numbers and TAC (Tables 61 and 63; Figures 50 and 53).

Our study showed an increase in the number of steps after training which showed how children engaged in walking outside the clinic. The findings also revealed an increase in TAC at the 1-month follow-up compared to pre-training, which showed the children had become more active—a claim supported by the LIFE-H questionnaire. Unfortunately, though the findings trend toward significance, they did not reach significance due to the small sample size (n = 5) but the data has medium to large effect size indicating a clinical significant change. Nonetheless, even with this small sample, all participants walked for longer distances and engaged in more activities after training, with mean increase in the number of steps and activity counts per day of 93% and 197%, respectively. In addition, all subjects sustained and further increased the improvement at follow-up except for the less-involved child, who experienced a minor decline at follow-up. This slight decline may be due to the personality of the child and his interests in activities that do not require motor activity, such as reading and drawing, in contrast to other subjects who were engaged in motor activities that required mobility and transportation.

No studies were found in the literature regarding activity increase as measured by the accelerometer after robotic-assisted training, but the literature did show that high repetitive practice leads to significant increases in use of the more involved limb in daily activities (Miltner et al., 1999; Taub et al., 1993; Taub, Uswatte, & Pidikiti, 1999). Additionally, the literature showed that active children are more likely to be active as adults, which leads to a longer and healthier life (Boreham & Riddoch, 2001). Being active and engaging in leisure activities is crucial for skill development, socialization, and enjoying life (Simpkins, Ripke, Huston, & Eccles, 2005). In summary, our findings from the accelerometer indicate a positive trend toward improving activity counts, which suggest that gains following skilled ankle robotic training transferred to functional ambulation in the community and home environment.

3. Participation Level Changes

The impairments at Body Function and Structures level have the potential to affect the child's participation level and quality of life (Calley et al., 2012). Participation is crucial for children because it impacts skills development, social relationships, self-competence, and overall mental and physical health (Forsyth & Jarvis, 2002; Caldwell & Gilbert, 2009). Children with CP experienced lower participation compared to their typically developing peers (Schenker, Coster, & Parush, 2005; Michelsen et al., 2009) due to restrictions in function and mobility as previously described (Calley et al., 2012; Tuzun, Eker, & Daskapan, 2004; Vargus-Adams, 2005; Moreau et al., 2016). The literature showed that children with CP experienced reduced participation in six school environments compared to their typically developing peers, including mealtime, toileting, transitions, transportation, classroom, and playground (Schenker, Coster, & Parush, 2005); therefore, enhanced participation is the main goal of rehabilitation (Flansbjer, Downham, & Lexell, 2006).

In this study, changes in participation levels were measured using the accelerometer and LIFE-H questionnaire at baseline (pre-test 2) and the one month follow-up. The results of this study demonstrated significant improvements in the total score on LIFE-H questionnaire (p= .020) with marginal improvements in subgroup scores, including communication (p=.139), community life (p= .717), education (p= .087), employment (p= .374), fitness (p= .147), housing (p=.210), interpersonal relationships (p=.374), mobility (p=.206), nutrition (p= .999), personal care (p= .141), recreation (p= .121), and responsibilities (p=.245). Unfortunately, these improvements were not significant and clinically meaningful when compared to the p-value and the MDC (Noreau et al., 2004), except for the total LIFE-H score. Community life, mobility, personal care, and housing were among the most improved scores on the LIFE-H questionnaire for all five participants and they have large effect size except for community life indicating important clinical changes. The changes among these physical categories connects with the improvement seen in impairments, physical functioning and mobility (Flansbjer, Downham, & Lexell, 2006). Another explanation for the change seen in these subgroup scores is the gender balance of our sample. The sample contained a majority of boys to girls (4:1) which effects the type of activity the children engage in. The literature showed that boys tend to participate in physical activities, while girls prefer social activities, which correlates to the majority of changes seen in community life, mobility, personal care, and housing domains (King et al., 2009; Law et al., 2006; Maher et al., 2007). Furthermore, age also impacts the activities in which children choose to participate. The literature showed that older children tend to participate more often in community activities compared to younger children (Klaas et al., 2010). Three of the five participants were nine, ten, and eleven years of age, which helps explains the change seen in community domain. Although it was not significant, the improvement in recreational activity participation is important, especially for children, because it helps them build friendship, develop their identity, enhance competence, and enhance their quality of life (Majnemer, 2006; McManus, Corcoran, & Perry, 2008). The literature showed higher levels of activity are associated with greater participation in leisure activities (Kerr et al., 2007; Kerr et al., 2008; King et al., 2006; King et al., 2009; Law et al., 2004; Majnemer et al., 2008).

The improvement seen in the questionnaire is supported by the accelerometer data that showed improvement in activity count. Little evidence was found in the literature to support changes in participation and quality of life following robotic training. Wire et al. (2011) conducted a study to investigate the effectiveness of two blocks of six biweekly training sessions using either robot-assisted body-weight-supported treadmill training (BWSTT) or unassisted BWSTT for improved quality of life in the multiple sclerosis population. They found physical component scores improved more in the robot-assisted BWSTT group as compared to the unassisted BWSTT group (Wire, Hatcher, & Lo, 2011). Cordo et al. (2009) found significant improvement in the sub-scores from their Stroke Impact Scale (SIS) questionnaire, including mobility ($p \leq .01$), and a trend toward improvement in the ADL ($p = .07$) category. Similar results were found by Burdea et al.

(2013), who documented significant improvement in quality of life in children with CP after 12 weeks of training on the RA CP system. Our subjects experienced similar improvement in quality of life, which was evidenced by the parent's report "of decreased fatigue and increased self-esteem, resulting in greater participation in leisure activity," in addition to the progress seen in activities including community life, mobility, personal care, and housing, as shown by the LIFE-H report. Every gain our participants made related to body structure and activity level added to the enhancement of the quality of life, as demonstrated by the increase in their activity counts as measured by the accelerometer (Table 61). Although not an objective of this investigation, this study showed evidence of increased subject-compliance and motivation to train due to the enjoyable quality of the robotic-assisted training and other built-in components, such as the ability to adjust task difficulty level and the auditory and visual feedback. Additionally, the participants were excited when challenged with a difficult and new game once they attained the maximum game difficulty. The literature showed that long intervention sessions need to constantly introduce new challenges in games with the pediatric population to sustain participant motivation (Huber et al., 2010). Finding motivational intervention methods is very important because it is not only increases the patient's enjoyment with training and compliance, but it enhances their active participation which is critical for motor learning and improving motor outcomes (Sakzewski, Ziviani, & Boyd, 2009; Novak et al., 2013; Mirelman, Patritti, Bonato & Deutsch, 2010). This is consistent with a study that found that three weeks of ankle robotic training (anklebot) with a high reward (HR) condition tremendously enhanced the efficacy of robotic training in post-stroke population as compared to a low reward (LR) condition (Jung, Diaz, & Macko, 2014). The results showed faster learning curves ($p = 0.05$), greater step length ($p = 0.05$), and smoother movements in the HR group which suggests combining HR with robotic therapy enhances the efficacy of robotics rehabilitation, thus accelerating the motor learning process to restore function faster. Our findings are consistent with Brütsch et al. (2011), who found that robot-assisted gait training with VR can improve active participation in children with different neurological gait disorders. This is further supported by positive results from Colombo et al. (2007), who found that three weeks of upper robot-aided training promote motivation and compliance to training in patients with chronic stroke due to the built-in qualities that include tailored difficulty level to suit each subject's need and continuous performance feedback.

In general, all gains among all three domains of the ICF were sustained at the 1-month follow-up, which supports our hypothesis that robot-assisted, task-specific ankle training may lead to a learning effect rather than a training effect. But there was some decline at the 1-month follow-up compared to 1 week post-training, which might indicate that our training dose is not enough. A higher frequency for a longer period of time might help to maintain the gain achieved at 1 week post-training.

Limitations

A number of limitations need to be considered before interpreting the results of this study. The small sample size (n=5) limited the ability to generalize the results. Many challenges were faced during recruitment that contributed to the small sample size: long evaluation times, which usually lasted between 60-90 minutes and created a significant time commitment for the families and children; a lack of participant compensation; and limited responses from physicians and therapists regarding the availability of potential participants. Another limitation is the sample selection because most participants were highly functioning (level I GMFCS) boys with right hemiparesis who do not represent the whole population of CP. Additionally, the lack of a control group may be a limiting factor because we have been unable to compare our training to results following no training or other treatment, which makes our clinical findings unclear. Although the two pre-tests provide some insight in this matter, having a control group would cast more light on the effectiveness of robotic-assisted training. Another limitation is that the two evaluators were aware of the training protocol, which may have increased researcher bias and weakened the study. Also, the anklebot's validity and reliability should be re-examined for the modified version, as this could be an extraneous variable. Lastly, the loss of one subject was an important factor considering the already small sample size.

Implication for Practice

The results of this study have revealed many implications for clinical practice, including information about a promising intervention that makes therapy and learning easier and more enjoyable for therapists and patients. It also showed the potential of anklebot intervention which only trained domain 1 to impact the other 2 domains. It also provides information about appropriate participants for this type of training. Although our sample is very small (n=5) and only includes children at level I-III at GMFCS, the results show that children with lower functioning ability (GMFCS III) may be better candidates for task-specific training compared to higher functioning kids because they are less mobile and more motivated to improve. Of course we need to be cautious to generate this finding without further investigation using a larger and more diverse sample. The study also suggests younger children may have a capacity for improvement through this training because they are more challenged by the games and their brains possess more plasticity than older children. This is evidenced by the huge improvement shown in the participants aged four and five comparing to the older participants. This study also provides knowledge to families of children with CP to help them make an informed decision about the most recent and appropriate treatment for their child. Furthermore, the therapeutic possibilities of this training may go beyond CP patients to other populations with neuromuscular deficits.

Implication for Future Research

This study has emphasized the need for further research into the use of robot-assisted task-specific ankle training in the treatment of children with CP. The author's recommendations for future research include larger sample sizes and a more heterogeneous sample that includes children with all level of GMFCS to better generalize the results of this study to the wider CP population. Also, a need exists for future studies that consider longer follow-up periods, varying doses and frequency of training, and comparisons with control and/or traditional therapies. Another suggestion that may impact the number of participants in future studies is considering scheduling conflicts (between the researcher and student assistant), the time of year when data is collected (avoiding summer time because the family will be less committed to the study), and encouraging participant compensation to increase sample sizes. Additionally, only a few studies have looked at activity and participation, which emphasizes the need for further investigation in these domains. Finally, this study neglected to capture qualitative data from the kids and their parents regarding how these improvements impacted the children's quality of life. Researchers tend to overlook this quality despite this being the core value of the rehabilitation, qualitative data collection could prove useful in future studies.

CHAPTER VI. CONCLUSION

Robot-assisted task-specific ankle training (anklebot) is a new intervention that possesses great therapeutic promise for the rehabilitation of children with CP. This study investigated the efficacy of the training on the deficits across the three domains of the ICF in children with CP. Although the intervention target only Body Function and Structures, improvement was seen at the other two domains. Finding an intervention that could impact activity and participation is important because it could decrease the demand for physical therapy services, thus reducing financial burden on the families of these children. The study also showed the potential of this new robotic technology in inducing neuroplasticity and learning effects that exceed the usual training effect of other traditional therapies. In addition to neuroplasticity, this study introduced an approach built upon well-known theories, including motor learning and dynamic system theory. The unique characteristics of the robotics allow children with CP to exercise with high repetitive movement without feeling fatigued or bored. Additionally, the property of the robotic to actively assist the subject during training helps reduce the physical load on therapists. This could enhance the training's efficiency since therapists focus more on observing and guiding the patients rather than assisting. This was evident by reducing the training session time at the end of our program, as the researcher played more of guiding role rather than assisting participants. Furthermore, this could help therapists see more patients, which could reduce wait time and enhance the overall efficacy of the physical therapy. Additionally, the results showed promising potential using robotic assisted training to improve gait with only one therapist, and this can lead to reduced personnel costs involved in manual assistance training, which usually requires up to two or three physical therapists (Nam et al., 2017). This study use the ICF as a multidimensional assessment framework to evaluate the current intervention which is important in determining optimal treatment planning. Furthermore, the study findings support the proposed technique of intervening distally to impact the proximal joint. The study also brought up the question of whether a more concentrated dose of training will get these children out of orthosis and back to normal growth rate. The accelerometer data points us to the strong potential that robotic assisted training can improve activity counts outside therapy, which helps maintain gains from therapy and reduces the children dependency on orthosis, thus increasing their ability to play and participate in recreational activities. Additionally, the challenge and novelty of the anklebot's different games improves patient compliance (up to 100%) and motivation and this resulted in better attention to performance and more cortical activity. Unlike traditional therapy that contains several training components, the robotic assistive training proposed by our study provided participants with a singular focus and few instructions making it easy for children to process, which contributed to the successful results. Furthermore, it gives hope to more involved children (levels II and III of GMFCS) with CP to improve their functional ability. With further study, the ankle robotic-assisted training has the potential to go beyond the studied population of CP and could be applied to populations with other neurological disorders.

APPENDICES

Appendix 1: IRB Approval

INDIANA UNIVERSITY

OFFICE OF THE VICE PRESIDENT FOR RESEARCH

Office of Research Compliance

To: PETER ANDREW ALTENBURGER
HEALTH/REHABILITATION SCIENCES

From:
[redacted]
Chair - IRB-02
Human Subjects Office
Office of Research Compliance – Indiana University

Date: June 16, 2015

RE: **NOTICE OF EXPEDITED APPROVAL - RENEWAL WITH AMENDMENT**

Protocol Title: A novel lower limb robot for children with cerebral palsy and drop foot

Study #: 1206008957R003

Funding Agency/Sponsor: N/A

Review Level: Expedited

Status: Approved | Submitted to IRB

Study Approval Date: June 15, 2015

Study Expiration Date: June 14, 2016

The Indiana University Institutional Review Board (IRB) IRB00000221 | IRB-02 recently reviewed the renewal with amendment associated with the above-referenced protocol. In compliance with (as applicable) 21 C.F.R. § 56.109 (e) and 46 C.F.R. § 46.109 (d), this letter serves as written notification of the IRB's determination.

The study is approved under Expedited Category (1) Category 1: Clinical studies of drugs and medical devices only when condition (a) or (b) is met. (a) Research on drugs for which an investigational new drug application (21 CFR Part 312) is not required. (Note: Research on marketed drugs that significantly increases the risks or decreases the acceptability of the risks associated with the use of the product is not eligible for expedited review.) (b) Research on medical devices for which (i) an investigational device exemption application (21 CFR Part 812) is not required; or (ii) the medical device is cleared/approved for marketing and the medical device is being used in accordance with its cleared/approved labeling. **(4)** Category 4: Collection of data through noninvasive procedures (not involving general anesthesia or sedation) routinely employed in clinical practice, excluding procedures involving x-rays or microwaves. Where medical devices are employed, they must be cleared/approved for marketing. (Studies intended to evaluate the safety and effectiveness of the medical device are not generally eligible for expedited review, including studies of cleared medical devices for new indications.) **(5)** Category 5: Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis). (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(4). This listing refers only to research that is not exempt.) **(6)** Category 6: Collection of data from voice, video, digital, or image recordings made for research purposes. **(7)** Category 7: Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.)

Approval of this study is based on your agreement to abide by the policies and procedures of the Indiana University Human Research Protection Program and does not replace any other approvals that may be required. Relevant policies and procedures governing Human Subject Research can be found at: http://researchadmin.iu.edu/HumanSubjects/hs_guidance.html.

As a reminder, IRB approval is required prior to implementing any changes or amendments in the protocol, regardless of how minor, except to eliminate immediate hazards to subjects. No changes to the informed consent document may be made without prior IRB approval.

If you submitted and/or are required to provide participants with an informed consent document, please ensure you are using the most recent version of the document to consent subjects.

The approval period is noted above. Failure to receive notification from the Human Subjects Office will not relieve you of your responsibility to ensure compliance with Federal Regulations regarding annual review [as applicable, 21 C.F.R. § 56.109(f) and 45 C.F.R. § 46.109(e)].

You should retain a copy of this letter and all associated approved study documents for your records. Please refer to the assigned study number and exact study title in future correspondence with our office. Additional information is available on our website at http://researchadmin.iu.edu/HumanSubjects/.

If your source of funding changes, you must submit an amendment to update your study documents immediately.

If you have any questions or require further information, please contact the Human Subjects Office via email at irb@iu.edu or via phone at (317)274-8289 (Indianapolis) or (812) 856-4242 (Bloomington).

You are invited, as part of ORA's ongoing program of quality improvement, to **participate in a short survey** to assess your experience and satisfaction with the IRB related to this approval. We estimate it will take you approximately **5 minutes to complete the survey**. The survey is housed on a Microsoft SharePoint secure site which requires CAS authentication. This survey is being administered by REEP; please contact us at reep@iu.edu if you have any questions or require additional information. Simply click on the link below, or cut and paste the entire URL into your browser to access the survey: https://www.sharepoint.iu.edu/sites/iu-ora/survey/Lists/Compliance/IRB_Survey/NewForm.aspx.

/enclosures

INDIANA UNIVERSITY

OFFICE OF THE VICE PRESIDENT FOR RESEARCH

Office of Research Compliance

To: PETER ANDREW ALTENBURGER
HEALTH/REHABILITATION SCIENCES

From: [redacted]
Chair - IRB-03
Human Subjects Office
Office of Research Compliance – Indiana University

Date: May 26, 2016

RE: **NOTICE OF EXPEDITED APPROVAL - RENEWAL**

Protocol Title:	A novel lower limb robot for children with cerebral palsy and drop foot
Study #:	1206008957R004
Funding Agency/Sponsor:	N/A
Review Level:	Expedited
Status:	Approved | Submitted to IRB

Study Approval Date: May 25, 2016

Study Expiration Date: May 24, 2017

The Indiana University Institutional Review Board (IRB) IRB00000228 | IRB-03 recently reviewed the renewal associated with the above-referenced protocol. In compliance with (as applicable) 21 C.F.R. § 56.109 (e) and 46 C.F.R. § 46.109 (d), this letter serves as written notification of the IRB's determination.

The study is approved under Expedited Category **(1)** Category 1: Clinical studies of drugs and medical devices only when condition (a) or (b) is met. (a) Research on drugs for which an investigational new drug application (21 CFR Part 312) is not required. (Note: Research on marketed drugs that significantly increases the risks or decreases the acceptability of the risks associated with the use of the product is not eligible for expedited review.) (b) Research on medical devices for which (i) an investigational device exemption application (21 CFR Part 812) is not required; or (ii) the medical device is cleared/approved for marketing and the medical device is being used in accordance with its cleared/approved labeling. **(5)** Category 5: Research involving materials (data, documents, records, or specimens) that have been collected, or will be collected solely for nonresearch purposes (such as medical treatment or diagnosis). (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(4). This listing refers only to research that is not exempt.) **(6)** Category 6: Collection of data from voice, video, digital, or image recordings made for research purposes. **(7)** Category 7: Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies. (NOTE: Some research in this category may be exempt from the HHS regulations for the protection of human subjects. 45 CFR 46.101(b)(2) and (b)(3). This listing refers only to research that is not exempt.), **with the following determinations, as applicable:**

Approval of this study is based on your agreement to abide by the policies and procedures of the Indiana University Human Research Protection Program and does not replace any other approvals that may be required. Relevant policies and procedures governing Human Subject Research can be found at: http://researchadmin.iu.edu/HumanSubjects/hs_policies.html.

As a reminder, IRB approval is required prior to implementing any changes or amendments in the protocol, regardless of how minor, except to eliminate immediate hazards to subjects. No changes to the informed consent document may be made without prior IRB approval.

If you submitted and/or are required to provide participants with an informed consent document, please ensure you are using the most recent version of the document to consent subjects.

The approval period is noted above. Failure to receive notification from the Human Subjects Office will not relieve you of your responsibility to ensure compliance with Federal Regulations regarding annual review [as applicable, 21 C.F.R. § 56.109(f) and 45 C.F.R. § 46.109(e)].

You should retain a copy of this letter and all associated approved study documents for your records. Please refer to the assigned study number and exact study title in future correspondence with our office. Additional information is available on our website at http://researchadmin.iu.edu/HumanSubjects/.

If your source of funding changes, you must submit an amendment to update your study documents immediately.

If you have any questions or require further information, please contact the Human Subjects Office via email at irb@iu.edu or via phone at (317)274-8289 (Indianapolis) or (812) 856-4242 (Bloomington).

You are invited, as part of ORA's ongoing program of quality improvement, to **participate in a short survey** to assess your experience and satisfaction with the IRB related to this approval. We estimate it will take you approximately **5 minutes to complete the survey**. The survey is housed on a Microsoft SharePoint secure site which requires CAS authentication. This survey is being administered by REEP; please contact us at reep@iu.edu if you have any questions or require additional information. Simply click on the link below, or cut and paste the entire URL into your browser to access the survey: https://www.sharepoint.iu.edu/sites/iu-ora/survey/Lists/Compliance/IRB_Survey/NewForm.aspx.

/enclosures

Appendix 2: Consent Form

INDIANA UNIVERSITY INFORMED CONSENT STATEMENT FOR

A Novel Lower Limb Ankle Robot for Children with Cerebral Palsy and Drop Foot

Your child is invited to participate in a research study to determine the effect of robotic therapy on improving ankle movement and function in children with Cerebral Palsy. Your child was selected as a possible subject because he/she is between the ages of 4-12 and has a diagnosis of hemiparesis. We ask that you read this form and ask any questions you may have before agreeing for your child to be in the study.

The study is being conducted by Madawi Alotaibi, PhD Student, Dr. Peter A. Altenburger and Dr. Ryan E. Cardinal, from the Department of Physical Therapy at Indiana University, School of Health and Rehabilitation Sciences.

STUDY PURPOSE

Your child is being asked to participate in this study, which involves robotic therapy to exercise the ankle in children with CP. The purpose of this research study is to test whether robotic therapy that gives repetitive practice of ankle movements helps to improve ankle function and strength in children with CP, which may then improve overall function and walking. We are asking your child to take part because he/she has limitations in ankle strength and coordination that can interfere with his/her functional mobility.

NUMBER OF PEOPLE TAKING PART IN THE STUDY:

If you agree for your child to participate, he/she will be one of 20 subjects who will be participating in this research study.

PROCEDURES FOR THE STUDY:

If you agree for your child to be in this study, your child will do the following things:

If you decide to enroll in the study, you will be asked to make a total of 16 trips to the IU Health Neurorehabilitation and Robotics Clinic where the study is taking place. Four of these visits will be testing sessions that will last for approximately 2 hours each. The other 12 visits will be treatment sessions where your child will work with the robot to improve his/her ankle function. Treatment sessions will last for 45-60 minutes. They will be scheduled 2 times per week depending upon availability in the Robotics Center.

Evaluations:
During testing sessions, your child will participate in a clinical evaluation much like therapy evaluations they've likely had in the past. We will ask questions regarding your child's history and will have questionnaires to be completed. We will perform several tests that will measure strength, range of motion, amount of spasticity and functional mobility, which include balance and walking. Some of the walking tests will include walking over a mat with sensors to analyze step sequences analysis. These tests will be repeated during all 4 testing sessions.

Therapy:
Within 1 week of the second pre-test testing session, your child will begin robotic treatment. Treatment sessions will be identical each visit. When your child arrives at the Robotics Clinic, his/her therapist will assist them in sitting in a chair. A plastic footplate will be fitted around your child's shoe. This footplate is securely supported so that no additional weight is felt by your child. Once secured, the anklebot will be calibrated so that it conforms to your child's movement ability. At the initiation of training, your child will be asked to control a cursor on a video monitor by moving his/her foot. Each training session will consist of 1056 movements of the cursor that will occur as part of three different fun game activities.

RISKS OF TAKING PART IN THE STUDY:|

Your child may experience mild fatigue or muscle soreness from the repeated practice of ankle movements during robotic therapy. Because the robot is a machine capable of independent motion, it is possible that the robot could accidentally lightly poke or bump your child. Numerous safety precautions have been implemented to prevent this from occurring, including multiple emergency shut-off switches. The treatment or procedure may involve risks that are currently unforeseeable.

BENEFITS OF TAKING PART IN THE STUDY:

You should not expect your child's condition to improve as a result of participating in this research. Benefits of robotic therapy for children with CP have not been studied yet, and this form of therapy may not be effective with children. However, potential benefits are that your child may improve the functional use of his/her ankle, including achieving improved balance and improved walking skills.

ALTERNATIVES TO TAKING PART IN THE STUDY:

The alternative to taking part in this study should you choose not to enroll or to discontinue at a later date is to discontinue robotic therapy and continue with your child's typical therapy plan.

CONFIDENTIALITY

Efforts will be made to keep your child's personal information confidential. We cannot guarantee absolute confidentiality. The only people who will know that your child is a research subject are members of the research team and, if appropriate, your physicians and nurses. No information about your child, or provided by your child, during the research will be disclosed to others without your written permission, except: if necessary to protect your rights or welfare, or if required by law.

When the results of the research are published or discussed in conferences, no information will be included that would reveal your child's identity. If photographs, videos, or audio-tape recordings of your child will be used for educational purposes, we will request your written authorization. Participation in this study does not hinge on your child agreeing to be photographed or filmed.

Organizations that may inspect and/or copy your research records for quality assurance and data analysis include groups such as the study investigator and his/her research associates, the Indiana University Institutional Review Board or it's designees, and (as allowed by law) state or federal agencies, specifically the Office for Human Research Protections (OHRP). Authorized representatives of the Food and Drug Administration (FDA) may need to review records of individual subjects. As a result, they may see your name; but they are bound by rules of confidentiality not to reveal your identity to others.

Your child will be assigned an ID number for the study. Only the investigators will have assess to the data. The data will be stored at the Neurorehabilitation & Biomechanics Research Laboratory located within the Neurorehabilitation and Robotics at IU Health Neuroscience Center. We plan to keep the data and images (photo & video) up to 5 years. In the unlikely event that somebody unauthorized will look into the data, he/she will only see your ID number with no names or other identifiers.

COSTS

There are no added costs to you/your child associated with participation in the study.

PAYMENT

Neither you nor your child will receive payment for taking part in this study.

COMPENSATION FOR INJURY

In the event of physical injury resulting from your child's participation in this research, necessary medical treatment will be provided to your child and billed to you as part of your medical expenses. Costs not covered by your health care insurer will be your responsibility. Also, it is your responsibility to determine the extent of your health care coverage. There is no program in place for other monetary compensation for such injuries. However, you are not giving up any legal rights or benefits to which you and your child are otherwise entitled.

CONTACTS FOR QUESTIONS OR PROBLEMS

For questions about the study or a research-related injury, contact Madawi Alotaibi [redacted] Dr. Peter Altenburger at [redacted] or Dr. Ryan Cardinal at [redacted]. If you cannot reach the researcher during regular business hours (i.e. 8:00AM-5:00PM), please call the IU Human Subjects Office at 317/278-3458 or 800/696-2949.

For questions about your child's rights as a research participant or to discuss problems, complaints or concerns about a research study, or to obtain information, or offer input, contact the IU Human Subjects Office at 317/278-3458 or 800/696-2949.

VOLUNTARY NATURE OF STUDY

Taking part in this study is voluntary. You may choose to not agree to allow your child to take part or you may request that your child leave the study at any time. Leaving the study will not result in any penalty or loss of benefits to which you and your child are entitled. Your decision whether or not to allow your child to participate in this study will not affect your current or future relations with the Department of Physical Therapy at Indiana University.

SUBJECT'S CONSENT

In consideration of all of the above, I give my consent to participate in this research study.

I will be given a copy of this informed consent document to keep for my records. I agree to take part in this study.

Subject's Printed Name:____________________________________

Subject's Signature:____**Date**:________________
(must be dated by the subject)

Printed Name of Person Obtaining Consent:__________________________

Signature of Person Obtaining Consent:____________________________**Date**:________________

If the study involves children who will be providing their assent on this consent document, rather than on an assent document, use the following signatures:

Printed Name of Parent:____________________________________

Signature of Parent:____**Date**:________________

Appendix 3: Assent Form

Study # 1206008957

Indiana University Assent to Participate in Research

A Novel Lower Limb Ankle Robot for Children with Cerebral Palsy and Drop Foot

We are doing a research study. A research study is a special way to learn about something. We are doing this research study because we are trying to find out more about how exercising with robots and video games might make you and children like you better. We would like to ask you to be in this research study.

Why am I being asked to be in this research study?

You are being asked to be in this research study because we think that if you do all of the foot exercises with the robot, it can help you move better, and then we can learn how to help other children like you move better.

What will happen during this research study?

We want to tell you about some things that might happen if you are in the study. This study will take place right here at the Robotics Center by the hospital. Each time you do the exercises with your feet it will take about 1 to 1 ½ hours. You will come to see us 16 times and do the exercises on the robot for 12 times.

If you want to be in this study, we will:

1. Ask you to answer some questions about yourself. Your parents/guardians may help you answer the questions
2. Do some tests that are similar to ones you have done before with your other therapists
3. Test how strong your leg muscles are
4. Test how far and fast you can walk
5. Test how your muscles work when you walk and use special cameras to tell us how your legs move when you walk.
6. Have you do exercises with your feet on the robot while playing video games

Are there any bad things that might happen during the research study?

Sometimes bad things happen to people who are in research studies. These bad things are called "risks". The bad things or risks of being in this study might be that your feet or legs feel tired from doing the exercises. Sometimes the robot might actually give you a little push or pull to help you move your legs around, but it won't hurt at all. And sometimes the straps that go around your legs and might pinch or pull a little bit, but we will make sure this doesn't happen very often.

Not all of these things may happen to you. None of them may happen. Things may happen that the doctors don't know about yet. If they do, we will make sure that you get help to deal with anything bad that might happen.

Are there any good things that might happen during the research study?

Sometimes good things happen to people who are in research studies. These good things are called "benefits". The good things or benefits of being in this study might be that you are able to walk and move your feet and legs better and even do other things better.

We don't know for sure if you will have any benefits or if you will get better. But we hope to learn something that will help other people someday.

Will I get money or payment for being in this research study?

You will not get any money for being in this research study but you might get rewards like stickers when you do a good job.

Who can I ask if I have any questions?

If you have any questions about this study, you can ask your parents or guardians or your doctor. Also, if you have any questions that you didn't think of now, you can ask us later. Since you will see us a lot on different days, you can ask us questions whenever you see us. Or you can ask your Mom or Dad and they can ask us at any time by calling us. The phone number for Madawi Alotaibi is [redacted] The phone number for Dr. Ryan Cardinal is [redacted] The phone number for Dr. Peter Altenburger is [redacted] And the phone number for your therapist at the Robotics Center is 317-963-7050.

What if I don't want to be in the study?

If you don't want to be in this study, you don't have to be. It is up to you. If you say you want to be in it and then you change your mind later, that's ok too. All you have to do is tell us that you don't want to be in it anymore. No one will be mad at you or upset with you and you won't get in trouble if you don't want to be in the study. Your doctors will continue to treat you whether or not you participate in this study.

My choice:

If I write my name on the line below, it means that I agree to be in this research study. You and your parents will be given a copy of this form after you have signed it.

Subject's Signature **Date**

Subject's Name

Signature of person obtaining assent **Date**

Name of person obtaining assent

Video/Photo Release Signature Of Research Subject Or Legal Representative

We also want to use a video camera during some of your robot sessions to educate people about cerebral palsy and robotics (perhaps at a school, university, or conference). Signing your name at the bottom means that you agree to let us take some pictures and videos and to show them. You will not be reimbursed for the photos or videotapes.

You don't need to sign the photo or video release to participate in this robot study. Participation in this study does not depend on you agreeing to be photographed or video-taped. You and your parents will be given a copy of this form after you have signed it.

______________________________ ______________

Subject's Signature **Date**

Appendix 4: Study's Flyer

Does Your Child Need Help With Walking?

Researchers at Indiana University seek children who have a diagnosis of cerebral palsy for a research study investigating the effects of Robot-Assisted Ankle training in improving walking abilities and participation in recreational activities.

Who is Eligible?

- Children diagnosed with CP
- Between 4 & 12 years old
- Have adequate cognitive and visual abilities
- Have mild spasticity at ankle
- With no fixed contractures

Qualified Participants Will Be:

- Refereed to Neurorehabilitation and Robotics at the IU Health Neuroscience Center
- Scheduled for 4 testing sessions to receive a clinical evaluation
- Provided 12 Robot-Assisted Ankle training sessions (2 x week) with 2 trained researchers

Neurorehabilitation & Robotic Clinic

At Indiana University Health Neuroscience Center

If you have any questions or if you would like to consider your child to participate in the study, please contact Madawi Alotaibi at [redacted] or mhalotai@umail.iu.edu

Appendix 5: List of Clinics

Clinic/Therapist	Contact Information
Andrew J. Brown Academy	F: 317-891-0908
Athletico physical therapy	F: 317-423-3506 E: IndianapolisMonumentCircle@athletico.com
Avondale Meadows Academy	E: kherron@avondalemeadowsacademy.org
Cerebral Palsy Clinic at Riley Hospital for Children Carolyn Lytle	E: clytle@iu.edu
Children's Therapy Connection	F: 317-288-7607
Christel House Academy	F: 317-783-4690
Community Hospital Pediatric Mindy Lewis	E: mlewis4@ecommunity.com
Easter Seals Crossroads	F: 317-466-2000
Eskenazi Hospital Pediatrics Christen Kring	E: christen.kring@eskenazihealth.edu
Hendricks Regional Health YMCA	F: 317-271-7600
IU Health Ball Memorial Hospital Josh McCormack	E: jmccormack@iuhealth.org
IU Health North Angie Eugenio	E: aeugenio@iuhealth.org
Pediatric Physiatrist at St. Vincent's/Peyton Manning Children's Hospital Dr. Denise Carpenter	F: 317-338-7673
PediPlay	F: 317-791-9001
Pediatric Physical Therapist at IU Health Capi Scheidler	E: cascheidler@gmail.com
Physical Therapy and Rehab - Washington A Department of Community Hospital East	F: 317-355-1331
Riley Hospital for Children Michelle Loftin, Physical Therapist	F: 317-944-1141 E: mloftin@iuhealth.org
School's Physiotherapist	E: scarneypt@gmail.com

Clinic/Therapist	Contact Information
Sara Davis	
School’s Physiotherapist Bree Pittman	E: Pittman.bree@gmail.com
Stroke clinic, IU Health Physicians - Riley Child Neurology Dr.Meredith R. Golomb	F: 317-944-3622
St.Vencent Pediatric Center Erin M. Patterson	F: 317-338-3550 E: EPATTERS@stvincent.org
St. Vincent Pediatric Therapies (Carmel)	F: 317-415-5895
St.Vencent Physical Therapy & Pediatric (Fisher) Jessica Prothero	F: 317-415-9138 E: JXPROTHE@stvincent.org
St. Vincent Erka Klene	E: EXKLENE@stvincent.org
The Children's TherAplay Foundation Hillary McCarley, Executive Director	F: 317-872-3234 E: hmccarley@childrenstheraplay.org
The Jackson Center	F: 317-834-0203
Uindy, Pediatrics Kathy Martin	E: kmartin@uindy.edu
United Cerebral Palsy Association of Greater Indiana	F: 317-632-3338 E: info@ucp.org

Appendix 6: Evaluation Form

Outcome Testing Session | Pre-test 1 | Pre-test 2 | Post-test | Follow-up

Subject ID:	Date of Birth:
Height:	Weight:
Diagnosis:	Evaluator's Name:
Age: 4-6 | 6-9 | 9-12	GMFCS Level: I | II | III
Date:	

Pediatric Balance Scale Test:

1. SITTING TO STANDING

INSTRUCTIONS: Hold arms up and stand up. Try not to use your hand for support.

( ) 4 able to stand without using hands and stabilize independently

( ) 3 able to stand independently using hands

( ) 2 able to stand using hands after several tries

( ) 1 needs minimal aid to stand or stabilize

( ) 0 needs moderate or maximal assist to stand

2. STANDING TO SITTING

INSTRUCTIONS: Please sit down slowly without use of hands.

( ) 4 sits safely with minimal use of hands

( ) 3 controls descent by using hands

( ) 2 uses back of legs against chair to control descent

( ) 1 sits independently but has uncontrolled descent

( ) 0 needs assist to sit

3. TRANSFERS

INSTRUCTIONS: Arrange chair(s) for pivot transfer. Ask the child to transfer one way toward a seat with armrests and one way toward a seat without armrests. You may use two chairs (one with and one without armrests) or a bed and a chair.

( ) 4 able to transfer safely with minor use of hands

( ) 3 able to transfer safely; definite need of hands

( ) 2 able to transfer with verbal cuing and/or supervision

( ) 1 needs one person to assist

( ) 0 needs two people to assist or supervise to be safe

4. STANDING UNSUPPORTED

INSTRUCTIONS: Please stand for 30 seconds without holding on or moving your feet.

( ) 4 able to stand safely for 30 seconds

( ) 3 able to stand 30 seconds with supervision

( ) 2 able to stand 15 seconds unsupported

( ) 1 needs several tries to stand 10 seconds unsupported

( ) 0 unable to stand 10 seconds unsupported

Time in seconds__________________

5. SITTING WITH BACK UNSUPPORTED BUT FEET SUPPORTED ON FLOOR OR ON A STOOL

INSTRUCTIONS: Please sit with arms folded on your chest for 30 seconds.

( ) 4 able to sit safely and securely for 30 seconds

( ) 3 able to sit 30 seconds under supervision or may require definite use of upper extremities to maintain sitting position

( ) 2 able to sit 15 seconds

( ) 1 able to sit 10 seconds

( ) 0 unable to sit 10 seconds without support

Time in seconds__________________

6. STANDING UNSUPPORTED WITH EYES CLOSED

INSTRUCTIONS: When I say close your eyes, I want you to stand still, close your eyes, and keep them closed until I say open.

( ) 4 able to stand 10 seconds safely

( ) 3 able to stand 10 seconds with supervision

( ) 2 able to stand 3 seconds

( ) 1 unable to keep eyes closed 3 seconds but stays steady

( ) 0 needs help to keep from falling

Time in seconds__________________

7. STANDING UNSUPPORTED WITH FEET TOGETHER

INSTRUCTIONS: Place your feet together and stand still without holding on.

( ) 4 able to place feet together independently and stand 30 seconds safely

( ) 3 able to place feet together independently and stand 30 seconds with supervision

( ) 2 able to place feet together independently but unable to hold for 30 seconds

( ) 1 needs help to attain position but able to stand 30 seconds feet together

( ) 0 needs help to attain position and unable to hold for 30 seconds

Time in seconds__________________

8. STANDING UNSUPPORTED ONE FOOT IN FRONT

INSTRUCTIONS: (DEMONSTRATE TO THE CHILD) Stand and place one foot directly in front of the other, heel to toe.

( ) 4 able to place foot tandem independently and hold 30 seconds

( ) 3 able to place foot ahead independently and hold 30 seconds

( ) 2 able to take small step independently and hold 30 seconds or required assistance to place foot in front, but can stand for 30 seconds.

( ) 1 needs help to step but can hold 15 seconds

( ) 0 loses balance while stepping or standing

Time in seconds__________________

9. STANDING ON ONE LEG

INSTRUCTIONS: Stand on one leg as long as you can without holding on.

( ) 4 able to lift leg independently and hold 10 seconds

( ) 3 able to lift leg independently and hold 5-9 seconds

( ) 2 able to lift leg independently and hold 3-4 seconds

( ) 1 tries to lift leg; unable to hold 3 seconds but remains standing independently

( ) 0 unable to try of needs assist to prevent fall

Time in seconds__________________

10. TURN 360 DEGREES

INSTRUCTIONS: Turn completely around in a full circle. Pause. Then turn a full circle in the other direction.

INITIALS: _________ SUBJECT ID: ___________ TEST TYPE: _____________

( ) 4 able to turn 360 degrees safely in 4 seconds or less each way

( ) 3 able to turn 360 degrees safely in one direction only in 4 seconds or less, completes turn in other direction requires more than 4 seconds

( ) 2 able to turn 360 degrees safely but slowly

( ) 1 needs close supervision or constant verbal cuing

( ) 0 needs assistance while turning

Time in seconds_________________

11. TURNING TO LOOK BEHIND OVER LEFT AND RIGHT SHOULDERS WHILE STANDING

INSTRUCTIONS: Please stand with your feet still, fixed in one place. Follow this object as I move it. Keep watching it as I move it, but don't move your feet.

( ) 4 looks behind/over each shoulder; weight shifts include trunk rotation

( ) 3 looks behind/over one shoulder with trunk rotation; weight shift in the oppsite direction is to the level of the shoulder; no trunk rotation

( ) 2 turns head to look to level of shoulder; no trunk rotation

( ) 1 needs supervision when turning; the chin moves greater than half the distance to the shoulder

( ) 0 needs assist to keep from losing balance or falling; movement of the chin is less than half the distance to the shoulder

12. PICK UP OBJECT FROM THE FLOOR FROM A STANDING POSITION

INSTRUCTIONS: Pick up the shoe/toy, which is in front of your feet.

( ) 4 able to pick up object safely and easily

( ) 3 able to pick up object but needs supervision

( ) 2 unable to pick up but reaches 2-5 cm (1-2 inches) from object and keeps balance independently

( ) 1 unable to pick up and needs supervision while trying

( ) 0 unable to try/needs assist to keep from losing balance or falling

13. PLACE ALTERNATE FOOT ON STEP OR STOOL WHILE STANDING UNSUPPORTED

INSTRUCTIONS: Place each foot alternately on the step/stool. Continue until each foot has touched the step/stool four times.

( ) 4 able to stand independently and safely and complete 8 steps in 20 seconds

( ) 3 able to stand independently and complete 8 steps in > 20 seconds

( ) 2 able to complete 4 steps without assistance, but requires close supervision

INITIALS: _________ SUBJECT ID: ___________ TEST TYPE: _____________

( ) 1 able to complete 2 steps; needs minimal assist

( ) 0 needs assistance to maintain balance or keep from falling/unable to try

Time in seconds_________________

14. REACHING FORWARD WITH OUTSTRETCHED ARM WHILE STANDING

INSTRUCTIONS: Lift arm to 90 degrees. Stretch out your fingers, make a fist, and reach forward as far as you can without moving your feet.

( ) 4 can reach forward confidently >25 cm (10 inches)

( ) 3 can reach forward >12 cm (5 inches), safely

( ) 2 can reach forward >5 cm (2 inches), safely

( ) 1 reaches forward but needs supervision

( ) 0 loses balance while trying/requires external support

ITEM DESCRIPTION	SCORE (0-4)	Seconds
1. Sitting to standing		
2. Standing to sitting		
3. Transfers		
4. Standing unsupported		
5. Sitting unsupported		
6. Standing with eyes closed		
7. Standing with feet together		
8. Standing with one foot in front		
9. Standing on one foot		
10. Turning 360 degrees		
11. Turning to look behind		
12. Retrieving object from floor		
13. Placing alternate foot on stool		
14. Reaching forward with outstretched arm		
Total Test Score (Maximum = 56)		

*** Interpretation: 41-56 = low fall risk 21-40 = medium fall risk 0 –20 = high fall risk

INITIALS: _________ SUBJECT ID: __________ TEST TYPE: ____________

A & P ROM:

Movement		Range	
		Right	Left
Ankle	Active planter flexion		
	Active dorsiflexion		
	Passive planter flexion		
	Passive dorsiflexion		
Subtalar	Active inversion		
	Active eversion		
	Passive inversion		
	Passive eversion		
Knee	Active knee flexion		
	Active knee extension		
	Passive knee flexion		
	Passive knee extension		
Hip	Active hip flexion		
	Active hip extension		
	Passive hip flexion		
	Passive hip extension		
	Active hip abduction		
	Active hip adduction		
	Passive hip abduction		
	Passive hip adduction		

INITIALS: __________ SUBJECT ID: ____________ TEST TYPE: ______________

Hand-held dynamometer for muscle testing of the lower extremities:

Joint/Muscle		Force (Pounds, Newtons or Kilograms)	
		Right	Left
Ankle	Dorsiflexors		
	Plantar flexors		
Subtalar	Evertors		
	Invertors		
Knee	Flexors		
	Extensors		
Hip	Flexors		
	Extensors		
	Abductor		
	Adductor		

INITIALS: ________ SUBJECT ID: __________ TEST TYPE: ____________

Tardieu Scale of Spasticity:

Joint/ Muscle	R2 (Passive full range of motion achieved when muscle is at rest and tested at V1 velocity)	X (Quality of muscle reaction)	R1 (Angle of catch seen at Velocity V3)	R2-R1
R Gastrocnemius				
L Gastrocnemius				
R Hamstring				
L Hamstring				

SCORING KEY FOR QUALITY OF MUSCLE REACTION (X):

0 No resistance throughout passive movement

1 Slight resistance throughout, with no clear catch at a precise angle

2 Clear catch at a precise angle, followed by release

3 Fatigable clonus (10secs) occurring at a precise angle

4 Unfatigable clonus (>10secs) occurring at a precise angle

5. Joint Immobile

INITIALS: __________ SUBJECT ID: ____________ TEST TYPE: ______________

Boyd and Graham Selective Motor Control Test:

Joint/ Muscle	Grade (0-4)
R Ankle dorsiflexors	
L Ankle dorsiflexors	

SCORING KEY:

0 Indicates no movement when asked to dorsiflex the ankle

1 Indicates partial dorsiflexion (using extensor hallucis longus and extensor digitorum longus)

2 Indicates dorsiflexion achieved using extensor hallucis longus, extensor digitorum longus and some tibialis anterior activity

3 Indicates dorsiflexion using tibialis anterior activity with hip and/or knee flexion

4 Indicates dorsiflexion achieved using tibialis anterior without hip and knee flexion

INITIALS: __________ SUBJECT ID: ____________ TEST TYPE: ______________

Gait Analysis:

☐ The test was performed If Not Explain Why ________________________________
____

Accelerometer:

☐ Actical Issued Actical No.________ Check out Date: ________________________
☐ Data were Retrieved From The Actical If Not Explain Why ___________________________
____

☐ Actical Returned Check in Date: ____________________________________

Assessment of Life Habits for Children (LIFE-H for Children):

☐ The Questionnaire Was Given To The Subject's Parents

☐ The Questionnaire Was Completed And Returned

INITIALS: ________ SUBJECT ID: __________ TEST TYPE: ___________

Appendix 7: Robotic Evaluation

Anklebot Protocol

Game	PF/DF	IN/EV	Combination
Ship	44 X 3= 132	44	44
Race	44 X 3= 132	44	
Soccer			44 X 3 = 132

Anklebot Measures

- **Ship**

		R Ankle	L Ankle
Robot initiation	PF/DF		
	IN/EV		
	Combination		
Accuracy	PF/DF		
	IN/EV		
	Combination		
Robot power	PF/DF		
	IN/EV		
	Combination		
Dwell time	PF/DF		

	IN/EV		
	Combination		
Movement smoothness	PF/DF		
	IN/EV		
	Combination		

- **Race**

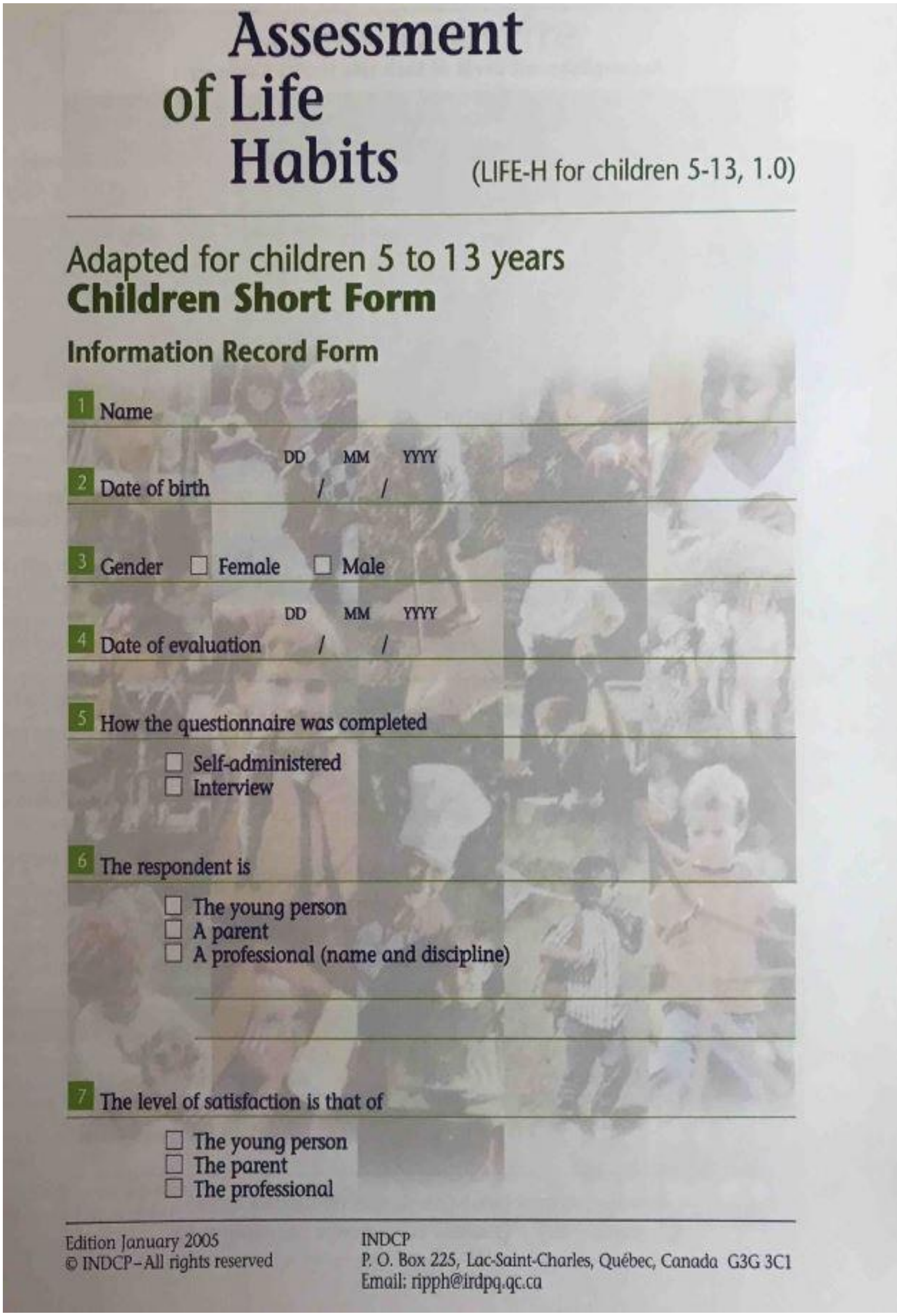
		R Ankle	**L Ankle**
Robot initiation	PF/DF		
	IN/EV		
Accuracy	PF/DF		
	IN/EV		
Robot power	PF/DF		
	IN/EV		
Dwell time	PF/DF		

	IN/EV		
Movement smoothness	PF/DF		
	IN/EV		

- **Soccer**

		R Ankle	L Ankle
Robot initiation	Combination		
Accuracy	Combination		
Robot power	Combination		
Dwell time	Combination		
Movement smoothness	Combination		

Appendix 8: LIFE-H for Children Form



Assessment of Life Habits

(LIFE-H for children 5-13, 1.0)

Adapted for children 5 to 13 years
Children Short Form

Information Record Form

1 Name

2 Date of birth DD / MM / YYYY

3 Gender ☐ Female ☐ Male

4 Date of evaluation DD / MM / YYYY

5 How the questionnaire was completed

- ☐ Self-administered
- ☐ Interview

6 The respondent is

- ☐ The young person
- ☐ A parent
- ☐ A professional (name and discipline)

7 The level of satisfaction is that of

- ☐ The young person
- ☐ The parent
- ☐ The professional

Edition January 2005

INDCP
P. O. Box 225, Lac-Saint-Charles, Québec, Canada G3G 3C1
Email: ripph@irdpq.qc.ca

Results
Accomplishment Level of Each Life Habits Category

Life Habits Categories	Number of Applicable Life Habits	Raw Score (Σ of scores)	Weighted Score (see formula)
Nutrition			
Fitness			
Personal Care			
Communication			
Housing			
Mobility			
Responsibilities			
Interpersonal Relationships			
Community Life			
Education			
Employment			
Recreation			
Total			/10

Life Habits Accomplishment Scale

Score	Difficulty Level	Assistance Type
9	No difficulty	No assistance
8	No difficulty	Assistive device (or adaptation)
7	With difficulty	No assistance
6	With difficulty	Assistive device (or adaptation)
5	No difficulty	Human assistance
4	No difficulty	Assistive device (or adaptation) and human assistance
3	With difficulty	Human assistance
2	With difficulty	Assistive device (or adaptation) and human assistance
1	Accomplished by a proxy	
0	Not accomplished	
N/A	Not applicable	

Accomplishment Level Calculation (Weighted Score)

$$(\sum \text{Scores} \times 10) \div (\text{Number of Applicable Life Habits} \times 9)$$

Questionnaire

Answer the following two questions. (Check the appropriate boxes.)

1 For each of the following life habits, indicate
A. How the young person usually accomplishes it, and
B. The type of assistance required to accomplish it.

2 For each of the following life habits, indicate your level of satisfaction with the way the young person accomplishes it.

* This refers to human assistance in addition to the assistance a young person of the same age usually requires.

N.B. Keep in mind that answers should reflect the young person's usual way of carrying out life habits.

	Question 1									Question 2					
	A Level of Accomplishment (Check only 1)					B Type of Assistance (Check 1 or more, as required)				Level of Satisfaction (Check only 1)					
	No difficulty	With difficulty	Accomplished by a proxy	Not accomplished	Not applicable	No assistance	Assistive device	Adaptation	Additional human assistance*	Very dissatisfied	Dissatisfied	More or less satisfied	Satisfied	Very satisfied	
Nutrition															
Selecting appropriate food for snacks and meals, according to taste or particular needs (quantity, type of food, etc.)															1.1
Taking part in meal preparation (including using certain kitchen appliances)															1.2
Eating meals (including using dishes and utensils, standard table manners, etc.)															1.3.1
Eating out at a restaurant (table service and fast-food)															1.3.2
Fitness															
Getting in and out of bed															2.1
Sleeping (comfort, duration, soundness)															2.2
Engaging in physical activities to maintain or improve physical health or fitness															2.3
Engaging in quiet activities that are relaxing or require attention (listening to music or a story, memory games, etc.)															2.4
Personal Care															
Attending to personal hygiene (washing, toothbrushing, hair combing, taking a bath or shower, etc.)															3.1
Using the toilet at home (including flushing method or device)															3.2.1
Using the toilet elsewhere than at home (including flushing method or device)															3.2.2

Answer the following two questions.
(Check the appropriate boxes.)

1 For each of the following life habits, indicate
A. How the young person usually accomplishes it, and
B. The type of assistance required to accomplish it.

2 For each of the following life habits, indicate your level of satisfaction with the way the young person accomplishes it.

* This refers to human assistance in addition to the assistance a young person of the same age usually requires.
N.B. Keep in mind that answers should reflect the young person's usual way of carrying out life habits.

	Question 1									Question 2					
	A Level of Accomplishment (Check only 1)					**B** Type of Assistance (Check 1 or more, as required)				Level of Satisfaction (Check only 1)					
	No difficulty	With difficulty	Accomplished by a proxy	Not accomplished	Not applicable	No assistance	Assistive device	Adaptation	Additional human assistance*	Very dissatisfied	Dissatisfied	More or less satisfied	Satisfied	Very satisfied	
Dressing and undressing the upper half of body (including fastening buttons and zippers and choosing clothes)															3.3.1
Dressing and undressing the lower half of body (including fastening buttons, zippers, and laces and choosing clothes)															3.3.2
Putting on, removing and maintaining assistive devices (orthotics, hearing aid, contact lenses, glasses, etc.)															3.3.3
Taking part in personal health care (first aid, following treatment instructions, medications, etc.)															3.4.1
Using services provided by a medical clinic, hospital, rehabilitation center, or community clinic (CLSC, CCAC)															3.4.2
Communication															
Communicating with an adult at home or in the community (expressing needs, having a conversation, etc.)															4.1.1
Communicating with a young person at home or in the community (expressing needs, having a conversation, etc.)															4.1.2
Communicating with a group of people at home or in the community (expressing ideas, having a conversation, etc.)															4.1.3
Communicating in writing (writing words, sentences, a short text, etc.)															4.2.1
Reading and understanding written information (words, books, pictographs, written instructions, signs, etc.)															4.2.2
Using a telephone at home															4.3.1
Using a computer															4.3.2
Using a television, a video recorder, a sound system, a Discman															4.3.3

4

Answer the following two questions. (Check the appropriate boxes.)

1 For each of the following life habits, indicate
A. How the young person usually accomplishes it, and
B. The type of assistance required to accomplish it.

2 For each of the following life habits, indicate your level of satisfaction with the way the young person accomplishes it.

* This refers to human assistance in addition to the assistance a young person of the same age usually requires.

N.B. Keep in mind that answers should reflect the young person's usual way of carrying out life habits.

	Question 1 — A Level of Accomplishment (Check only 1)					Question 1 — B Type of Assistance (Check 1 or more, as required)				Question 2 — Level of Satisfaction (Check only 1)					
	No difficulty	With difficulty	Accomplished by a proxy	Not accomplished	Not applicable	No assistance	Assistive device	Adaptation	Additional human assistance*	Very dissatisfied	Dissatisfied	More or less satisfied	Satisfied	Very satisfied	
Housing															
Taking part in housekeeping tasks (light cleaning, making bed, tidying up, etc.)															5.2.1
Taking part in maintaining the grounds (lawncare, snow removal, etc.)															5.2.2
Entering and exiting the home															5.3.1
Moving around within the home															5.3.2
Using the furniture and equipment at home (table, storage space, lighting, outdoor play equipment, etc.)															5.3.3
Moving around outside the home (backyard, grounds)															5.3.4
Mobility															
Moving around on streets and sidewalks (including crossing streets)															6.1.1
Moving around on slippery or uneven surfaces (snow, ice, grass, gravel, etc.)															6.1.2
Riding a bicycle (as means of transportation, for leisure, etc.)															6.2.1
Being a passenger in a vehicle (automobile, bus, taxi, etc.) (adapted transportation is considered an adaptation)															6.2.2
Responsibilities															
Recognizing the value of coins and bills and using them correctly															7.1.1
Managing pocket money (savings, small purchases, etc.)															7.1.2
Using a bank card and an automatic teller machine (ATM)															7.1.3
Shopping, running errands (choosing and paying for merchandise, access to stores, etc.)															7.1.4

5

Answer the following two questions.
(Check the appropriate boxes.)

1 For each of the following life habits, indicate
A. How the young person usually accomplishes it, and
B. The type of assistance required to accomplish it.

2 For each of the following life habits, indicate your level of satisfaction with the way the young person accomplishes it.

* This refers to human assistance in addition to the assistance a young person of the same age usually requires.
N.B. Keep in mind that answers should reflect the young person's usual way of carrying out life habits.

	Question 1: A Level of Accomplishment (Check only 1)					Question 1: B Type of Assistance (Check 1 or more, as required)				Question 2: Level of Satisfaction (Check only 1)					
	No difficulty	With difficulty	Accomplished by a proxy	Not accomplished	Not applicable	No assistance	Assistive device	Adaptation	Additional human assistance*	Very dissatisfied	Dissatisfied	More or less satisfied	Satisfied	Very satisfied	
Respecting other people's property and rights (personal effects, rules of conduct, etc.)															7.2.1
Taking charge of himself/herself, standing up for rights															7.2.2
Helping out at home (doing a service for parents or other family members, etc.)															7.3
Interpersonal Relationships															
Maintaining a loving relationship with parents															8.1.1
Maintaining a loving relationship with other members of the immediate family (sisters, brothers, etc.)															8.1.2
Maintaining a loving or social relationship with other relatives (grandparents, cousins, etc.)															8.1.3
Being involved or participating in sexual awakening activities (information, discussions, physical contact etc.)															8.1.4
Maintaining friendly or social ties with other young people (school, recreational activities, etc.)															8.2.1
Maintaining social ties with adults (teachers, instructors, etc.)															8.2.2
Community Life															
Participating in the activities of community groups, student associations, etc. (scouts, class committees, various organizations, etc.)															9.1.1
Participating in religious or spiritual activities															9.1.2
Education															
Getting to school, entering and moving around in the school and schoolyard (including carrying a schoolbag)															10.1
Taking part in learning activities at school (workshops, classes, assignments, exams, etc.)															10.2

6

Answer the following two questions. (Check the appropriate boxes.)

1 For each of the following life habits, indicate
A. How the young person usually accomplishes it, and
B. The type of assistance required to accomplish it.

2 For each of the following life habits, indicate your level of satisfaction with the way the young person accomplishes it.

* This refers to human assistance in addition to the assistance a young person of the same age usually requires.
N.B. Keep in mind that answers should reflect the young person's usual way of carrying out life habits.

	Question 1									Question 2					
	A Level of Accomplishment (Check only 1)					B Type of Assistance (Check 1 or more, as required)				Level of Satisfaction (Check only 1)					
	No difficulty	With difficulty	Accomplished by a proxy	Not accomplished	Not applicable	No assistance	Assistive device	Adaptation	Additional human assistance*	Very dissatisfied	Dissatisfied	More or less satisfied	Satisfied	Very satisfied	
Taking specialized classes (physical education, music, etc.)															10.3
Using school facilities (cafeteria, schoolyard, gymnasium, daycare, etc.)															10.4
Doing homework															10.5
Taking part in school activities (extra-curricular, outings, field days, etc.)															10.6
Work															
Performing small paid or unpaid jobs (babysitting, delivering newspapers, mowing lawns etc.)															11.3.1
Recreation															
Taking part in sports or recreational activities (sports and games, outdoor recreation, etc.)															12.1.1
Playing individual or group games indoors or outdoors (card games, ball games, video games, etc.)															12.1.2
Attending sporting events (hockey, baseball, etc.)															12.1.3
Taking part in artistic, cultural, or craft activities (music, dance, arts and crafts, etc.)															12.2.1
Attending artistic or cultural events (concerts, movies, theater, etc.)															12.2.2
Taking part in tourist activities (traveling, visiting natural or historic sites, etc.)															12.2.3
Getting to, entering, and moving around in local recreational facilities															12.2.4
Using local recreational facilities (library, municipal recreation center, etc.)															12.2.5

Comments

Use the following lines for general comments or remarks related specifically to one or more of the following topics regarding the young person:

a) The level of accomplishment
b) The type of assistance required
c) The level of satisfaction

or for general comments pertaining to any other aspect of this questionnaire.

8

Appendix 9: Prescreening Form

Neurorehabilitation and Biomechanics Research Laboratory

IU Health Neuroscience Center

The Effectiveness of Anklebot on Motor Impairments of Children with Cerebral Palsy

Subject ID: ____________________

Protocol

1. Patients will be refereed to Neurorehabilitation and Robotics at IU Health Neuroscience Center from physicians, based on functional needs.
2. Prescreening will be completed through telephone conversations with the patients' parents, who have been previously referred to the Robotics Clinic.
3. Following prescreening, potential subjects will be scheduled for the testing sessions.
4. Subject will be scheduled for baseline outcome testing, conducted 1 month prior to initial Anklebot training session.
5. Subject will be return for the second pre testing session, conducted 1 week prior to initial Anklebot training session.
6. Subject will participate in 12 Anklebot training sessions (2 x week) with 2 trained physical therapy students within the Neurorehabilitation and Biomechanics Research Laboratory.
7. Following 12^{th} Anklebot training session, subject returns within 1 week for post-intervention outcome testing.
8. Subject returns 1 month following post-intervention outcome testing to participate in 1 month follow-up outcome testing.

Outcome Measures

1. Gross Motor Functional Classification System (GMFCS)
2. Pediatric Balance Scale (PBS)
3. AROM & PROM
   a. Ankle plantarflexion/ dorsiflexion (R & L)
   b. Ankle eversion/inversion (R & L)
   c. Knee flexion/extension (R & L)
   d. Hip flexion/extension (R & L)
   e. Hip abduction/adduction (R & L)
4. Hand-held dynamometer for muscle testing of the lower extremities
   a. Ankle plantarflexion/ dorsiflexion (R & L)
   b. Ankle eversion/inversion (R & L)
   c. Knee flexion/extension (R & L)
   d. Hip flexion/extension (R & L)
   e. Hip abduction/adduction (R & L)
5. Tardieu Scale of spasticity
   a. Gastrocnemius (R & L)
   b. Hamstring (R & L)

INITIALS: ________ SUBJECT ID: __________ DATE: __________

6. Boyd and Graham selective motor control test
    a. Ankle (R & L)
7. Assessment of Life Habits for Children (LIFE-H for Children)
8. Accelerometer
    a. To be given to participants and worn at the 2nd pre-testing session and return back to lab at the 1 month follow-up outcome testing.
        i. EE spent in light physical activity
        ii. EE spent in moderate physical activity
        iii. EE spent in vigorous physical activity
        iv. Total EE
        v. Number of steps
        vi. Total activity counts (TAC)
9. Gait mat analysis
    a. Velocity
    b. Step length
    c. Cadence
    d. Swing time
    e. Stance time
    f. Single support time
10. Anklebot measures
    a. Performed after each training session
        i. Robot initiation (R & L)
        ii. Accuracy (R & L)
        iii. Robot power (R & L)
        iv. Dwell time (R & L)
        v. Movement smoothness (R & L)
11. Ultrasound for Achilles tendon (AT), tibialis anterior (TA) and gastrocnemius muscles

Inclusion Criteria Checklist

Protocol Title: The Effectiveness of Robot-Assisted, Task-Specific Ankle Training in Reducing Motor Impairment and Improving Motor Function for Children with Cerebral Palsy (CP)

Subject ID: ____________________

Date of Birth: ____________________ **Date of Evaluation:** ____________________

Person completing form: ____________________

Principal Investigator's Name: ____________________

Inclusion Criteria (list each criteria)	**Yes**	**No**	**Supporting Documentation*** (all must be "yes" for eligibility)
1. Subject has a diagnosis of Cerebral Palsy (Any neurological insult occurring before, during, or up to 2 years after birth resulting in a movement disorder)			
2. Subject is between the ages of 4 and 12 years			
3. Subject has adequate cognitive and visual abilities to understand and perform the task			
4. Subject has Tardieu spasticity grade less than or equal to three at ankle plantar flexor muscles			
5. Subject has the ability to independently stand and walk, with or without assistance.			
6. Subject has level I–III in the Gross Motor Function Classification System (GMFCS)			

INITIALS: ________ SUBJECT ID: ________ DATE: ________

Exclusion Criteria (list each criteria)	**Yes**	**No**	**Supporting Documentation*** (all must be "no" for eligibility)
1. Subject is non-ambulatory			
2. Subject has bone instability, open skin lesions, circulatory problems, cardiac contraindications to physical activity, vascular disorders of the lower limbs, or extremely disproportionate growth of the legs.			
3. Subject has fixed contractures.			
4. Subject has significant visual or hearing loss.			
5. Subject does not have sufficient ability to follow directions and be cooperative during a 60-minute evaluation or treatment sessions.			
6. Subject does not have the ability to reliably communicate discomfort, pain, or fear during treatment sessions.			
7. Subject will not comply with full protocol.			
8. Subject is too small or too large to fit the Anklebot properly			
Subject meets all the inclusion criteria and did not meet any exclusion criteria. Therefore, the study's eligibilities were confirmed for this subject's enrollment.	__ Yes, subject can be enrolled		___ No, and subject is a screen failure.

INITIALS: _______ SUBJECT ID: _________ DATE: _________

		___ No, but was enrolled with IRB's approval and /or sponsor's waiver.
Please explain if any issues, exceptions, or waivers occur:		

MOTOR MILESTONES:

If atypical or delayed, list your child's age at the time of demonstration for the following:

Rolling over: ________________ Sitting up: ____________________ Crawling: __________________

Cruising: ______________________________ Walking: ______________________________________

Other/Comments: ____

____

OTHER THERAPIES:

Does your child take any prescription or nonprescription medications? ☐ Yes ☐ No If yes, specify____

____

Does your child currently receive any other therapy services? ☐ Yes ☐ No

If yes, please list type and where services are provided (or have been previously) as well as the therapist and the frequency:

Type of service	Location	Therapist	Frequency

REFERENCES

Aagaard, P., Andersen, J. L., Dyhre-Poulsen, P., Leffers, A. M., Wagner, A., Magnusson, S. P., Halkjaer-Kristensen, J., & Simonsen, E. B. (2001). A mechanism for increased contractile strength of human pennate muscle in response to strength training: changes in muscle architecture. *The journal of physiology,* 534(2), 613-623.

Abel, M. F., & Damiano, D. L. (1996). Strategies for increasing walking speed in diplegic cerebral palsy. *Journal of Pediatric Orthopaedics*, 16(6), 753-758.

Abel, M. F., Damiano, D. L., Blanco, J. S., Conaway, M., Miller, F., Dabney, K., Sutherland, D., Chambers, H., Dias, L., Sarwark, J., & Killian, J. (2003). Relationships among musculoskeletal impairments and functional health status in ambulatory cerebral palsy. *Journal of Pediatric Orthopaedics*, 23(4), 535-541.

Adolph, K. E., & Berger, S. E. (2006). *Motor development. Handbook of child psychology*.

Agency for Healthcare Research and Quality (AHRQ). (2012, October). *Re: Closing the Quality Gap: Revisiting the State of the Science Series: Quality Improvement Measurement of Outcomes for People with Disabilities [Structured Abstract]*. Retrieved from http://www.ahrq.gov/clinic/tp/gapdisouttp.htm

Aharonson, V., & Krebs, H. I. (2012). Prediction of response to robot-aided motor neuro-rehabilitation of children with cerebral palsy. *Biomedical Signal Processing and Control*, *7*(2), 180-184.

Aisen, M. L., Krebs, H. I., Hogan, N., McDowell, F., & Volpe, B. T. (1997). The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. *Archives of neurology*, *54*(4), 443-446.

Alhusaini, A.A., Dean, C.M., Crosbie, J., et al. (2010). Evaluation of spasticity in children with cerebral palsy using Ashworth and Tardieu Scales compared with laboratory measures. *J Child Neurol*, 25:1242–7.

Allen, P. E., Jenkinson, A., Stephens, M. M., & O'brien, T. (2000). Abnormalities in the uninvolved lower limb in children with spastic hemiplegia: the effect of actual and functional leg-length discrepancy. *Journal of Pediatric Orthopaedics*, 20(1), 88.

Alves, J. W., Alday, R. V., Ketcham, D. L., & Lentell, G. L. (1992). A comparison of the passive support provided by various ankle braces. *Journal of Orthopaedic & Sports Physical Therapy*, 15(1), 10-18.

American Physical Therapy Association (APTA). (2015). *Vision 2020*. Reserved from http://www.apta.org/Vision2020/

Anderson, D. L., Sanderson, D. J., & Hennig, E. M. (1995). The role of external nonrigid ankle bracing in limiting ankle inversion. *Clinical Journal of Sport Medicine*, 5(1), 18-24.

Andersson, C., Grooten, W., Hellsten, M., Kaping, K., & Mattsson, E. (2003). Adults with cerebral palsy: walking ability after progressive strength training. *Developmental medicine and child neurology*, 45(4), 220-228.

Ansari, N.N., Naghdi, S., et al. (2008). "The Modified Tardieu Scale for the measurement of elbow flexor spasticity in adult patients with hemiplegia." *Brain Injury*, 22(13-14): 1007-1012.

Anttila, H., Autti-Rämö, I., Suoranta, J., Mäkelä, M., & Malmivaara, A. (2008). Effectiveness of physical therapy interventions for children with cerebral palsy: a systematic review. *BMC pediatrics*, 8(1), 14.

APTA. (2014). *Report Predicts Coming PT, PTA Shortage in US*. Retrieved from http://www.apta.org/PTinMotion/News/2014/9/3/ConferenceBoardLaborStats/

Arnold, A. S., & Delp, S. L. (2005). Computer modeling of gait abnormalities in cerebral palsy: application to treatment planning. *Theoretical Issues in Ergonomics Science*, 6(3-4), 305-312.

Ayalon, M., Ben-Sira, D., Hutzler, Y., & Gilad, T. (2000). Reliability of isokinetic strength measurements of the knee in children with cerebral palsy. *Developmental medicine and child neurology*, 42(6), 398-402.

Backhaus, M., Burmester, G. R., Gerber, T. H., Grassi, W., Machold, K. P., Swen, W. A., Wakefield, R.J. and & Manger, B. (2001). Guidelines for musculoskeletal ultrasound in rheumatology. *Annals of the rheumatic diseases*, 60(7), 641-649.

Ballaz, L., Plamondon, S., & Lemay, M. (2010). Ankle range of motion is key to gait efficiency in adolescents with cerebral palsy. *Clinical Biomechanics*, 25(9), 944-948.

Banala, S. K., Kim, S. H., Agrawal, S. K., & Scholz, J. P. (2009). Robot assisted gait training with active leg exoskeleton (ALEX). *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 17(1), 2-8.

Bandholm, T., Magnusson, P., Jensen, B. R., & Sonne-Holm, S. (2009). Dorsiflexor muscle-group thickness in children with cerebral palsy: relation to cross-sectional area. *NeuroRehabilitation*, 24(4), 299-306.

Baram, Y., & Lenger, R. (2012). Gait improvement in patients with cerebral palsy by visual and auditory feedback. Neuromodulation: *Technology at the Neural Interface*, 15(1), 48-52.

Barber, L. A., & Boyd, R. N. (2016). Growing muscles in children with cerebral palsy. *Developmental Medicine & Child Neurology*, 58(5), 431-432.

Barber, L., Hastings-Ison, T., Baker, R., Barrett, R. O. D., & Lichtwark, G. (2011). Medial gastrocnemius muscle volume and fascicle length in children aged 2 to 5 years with cerebral palsy. *Developmental medicine & child neurology*, 53(6), 543-548.

Bar-Haim, S., Harries, N., Belokopytov, M., Frank, A., Copeliovitch, L., Kaplanski, J., & Lahat, E. (2006). Comparison of efficacy of Adeli suit and neurodevelopmental treatments in children with cerebral palsy. *Dev Med Child Neurol*, 48(5), 325-330.

Bartlett, D. J., & Palisano, R. J. (2002). Physical therapists' perceptions of factors influencing the acquisition of motor abilities of children with cerebral palsy: implications for clinical reasoning. *Physical Therapy, 82*(3), 237-248.

Basmajian, J. V., Gowland, C. A., Finlayson, M. A., Hall, A. L., Swanson, L. R., Stratford, P. W., et al. (1987). Stroke treatment: comparison of integrated behavioral-physical therapy vs traditional physical therapy programs. *Archives of Physical Medicine and Rehabilitation*, 68(5 Pt 1), 267-272.

Bax, M., Goldstein, M., Rosenbaum, P., Leviton, A., Paneth, N., Dan, B., et al. (2005). Proposed definition and classification of cerebral palsy, April 2005. *Dev Med Child Neurol*, 47(08), 571-576.

Beckung, E., Hagberg, G., Uldall, P., & Cans, C. (2008). Probability of walking in children with cerebral palsy in Europe. *Pediatrics, 121*(1), e187-192. doi: peds.2007-0068 [pii]10.1542/peds.2007-0068

Bell, K. J., Ounpuu, S., DeLuca, P. A., & Romness, M. J. (2002). Natural progression of gait in children with cerebral palsy. *Journal of Pediatric Orthopaedics*, 22(5), 677-682.

Beretta, E., Romei, M., Molteni, E., Avantaggiato, P., & Strazzer, S. (2015). Combined robotic-aided gait training and physical therapy improve functional abilities and hip kinematics during gait in children and adolescents with acquired brain injury. *Brain injury*, 29(7-8), 955-962.

Berger, W., Quintern, J., & Dietz, V. (1982). Pathophysiology of gait in children with cerebral palsy. *Electroencephalography and clinical neurophysiology*, 53(5), 538-548.

Berman, A.T., Zarro, V.J., Bosacco, S.J., Israelite, C. (1987). Quantitative gait analysis after unilateral or bilateral total knee replacement. *J Bone Joint Surg Am*, 69(9):1340-5.

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Berry, E. T., Giuliani, C. A., & Damiano, D. L. (2004). Intrasession and intersession reliability of handheld dynamometry in children with cerebral palsy. *Pediatric Physical Therapy*, 16(4), 191-198.

Bianchi, S., Martinoli, C., Abdelwahab, I. F., Derchi, L. E., & Damiani, S. (1998). Sonographic evaluation of tears of the gastrocnemius medial head (" tennis leg"). *Journal of ultrasound in medicine*, 17(3), 157-162.

Biernaskie, J., Chernenko, G., & Corbett, D. (2004). Efficacy of rehabilitative experience declines with time after focal ischemic brain injury. *Journal of Neuroscience*, 24, 1245–1254.

Bjornson, K. F., Belza, B., Kartin, D., Logsdon, R., & McLaughlin, J. F. (2007). Ambulatory physical activity performance in youth with cerebral palsy and youth who are developing typically. *Physical Therapy*, 87(3), 248-257.

Bland, D. C., Prosser, L. A., Bellini, L. A., Alter, K. E., & Damiano, D. L. (2011). Tibialis anterior architecture, strength, and gait in individuals with cerebral palsy. *Muscle & nerve*, 44(4), 509-517.

Blaya, J., & Herr, H. (2004). Adaptive control of a variable-impedance ankle-foot orthosis to assist drop-foot gait. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 12(1), 24-31.

Bloomquist, K., Langberg, H., Karlsen, S., Madsgaard, S., Boesen, M., & Raastad, T. (2013). Effect of range of motion in heavy load squatting on muscle and tendon adaptations. *European journal of applied physiology*, 113(8), 2133-2142.

Bohannon, R. W. (1986). Strength of lower limb related to gait velocity and cadence in stroke patients. *Physiotherapy Canada,* 38(4), 204-206.

Bohannon, R. W. (1989). Selected determinants of ambulatory capacity in patients with hemiplegia. *Clinical Rehabilitation*, 3(1), 47-53.

Boian, R. F., Deutsch, J. E., Lee, C. S., Burdea, G. C., & Lewis, J. (2003, March). Haptic effects for virtual reality-based post-stroke rehabilitation. *In Haptic Interfaces for Virtual Environment and Teleoperator Systems*, 2003. HAPTICS 2003. Proceedings. 11th Symposium on (pp. 247-253). IEEE.

Boian, R. F., Lee, C. S., Deutsch, J. E., Burdea, G., & Lewis, J. A. (2002). Virtual reality-based system for ankle rehabilitation post stroke. In *Proc. 1st Int. Workshop Virtual Reality Rehabilitation* (pp. 77-86).

Boreham, C., & Riddoch, C. (2001). The physical activity, fitness and health of children. *Journal of sports sciences,* 19(12), 915-929.

Borggraefe, I., Kiwull, L., Schaefer, J. S., Koerte, I., Blaschek, A., Meyer-Heim, A., & Heinen, F. (2010). Sustainability of motor performance after robotic-assisted treadmill therapy in children: an open, non-randomized baseline-treatment study. *European journal of physical and rehabilitation medicine*,46(2), 125-131.

Borggraefe, I., Schaefer, J. S., Klaiber, M., Dabrowski, E., Ammann-Reiffer, C., Knecht, B., et al. (2010). Robotic-assisted treadmill therapy improves walking and standing performance in children and adolescents with cerebral palsy. *European journal of paediatric neurology,* 14(6), 496-502.

Boyd, L., & Winstein, C. (2006). Explicit information interferes with implicit motor learning of both continuous and discrete movement tasks after stroke. *Journal of Neurologic Physical Therapy*, 30, 46–57.

Boyd, R.N., & Graham, H.K. (1999). Objective measures of clinical findings in the use of botulinum toxin type A for the management of children with cerebral palsy. *Eur J Neurol*, 6 (Suppl. 4): 523–535.

Brehm, M. A., Harlaar, J., & Schwartz, M. (2008). Effect of ankle-foot orthoses on walking efficiency and gait in children with cerebral palsy. *Journal of rehabilitation medicine*, 40(7), 529-534.

Brown, M., & Gordon, W. (1987). Impact of impairments on activity patterns of children. *Archives of Physical Medicine and Rehabilitation*, 68, 828-832.

Brütsch, K., Koenig, A., Zimmerli, L., Mérillat-Koeneke, S., Riener, R., Jäncke, L., van Hedel, H.J. & Meyer-Heim, A. (2011). Virtual reality for enhancement of robot-assisted gait training in children with neurological gait disorders. *Journal of Rehabilitation Medicine*, 43(6), 493-499.

Buckon, C. E., Thomas, S. S., Jakobson-Huston, S., Moor, M., Sussman, M., & Aiona, M. (2001). Comparison of three ankle–foot orthosis configurations for children with spastic hemiplegia. *Developmental medicine and child neurology*, 43(6), 371-378.

Burdea, G. C., Cioi, D., Kale, A., Janes, W. E., Ross, S. A., & Engsberg, J. R. (2013). Robotics and gaming to improve ankle strength, motor control, and function in children with cerebral palsy—a case study series. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 21(2), 165-173.

Burgar, C. G., Lum, P. S., Shor, P. C., & Van der Loos, H. M. (2000). Development of robots for rehabilitation therapy: the Palo Alto VA/Stanford experience. *Journal of rehabilitation research and development*, 37(6), 663-674.

Burns, J., Redmond, A., Ouvrier, R., & Crosbie, J. (2005). Quantification of muscle strength and imbalance in neurogenic pes cavus, compared to health controls, using hand-held dynamometry. *Foot & ankle international*, 26(7), 540-544.

Burtner, P. A., Woollacott, M. H., Craft, G. L., & Roncesvalles, M. N. (2007). The capacity to adapt to changing balance threats: a comparison of children with cerebral palsy and typically developing children. *Developmental Neurorehabilitation*, 10(3), 249-260.

Bütefisch, C., Hummelsheim, H., Denzler, P., & Mauritz, K. H. (1995). Repetitive training of isolated movements improves the outcome of motor rehabilitation of the centrally paretic hand. *Journal of the neurological sciences*, 130(1), 59-68.

Butler, C., & Darrah, J. (2001). Effects of neurodevelopmental treatment (NDT) for cerebral palsy: an AACPDM evidence report. *Developmental Medicine & Child Neurology*, 43(11), 778-790.

Butte, N. F., Puyau, M. R., Adolph, A. L., Vohra, F. A., & Zakeri, I. S. S. A. (2007). Physical activity in nonoverweight and overweight Hispanic children and adolescents. *Medicine and Science in Sports and Exercise*, 39(8), 1257-1266.

Byl, N., Roderick, J., Mohamed, O., Hanny, M., Kotler, J., Smith, A., Tang, M. & Abrams, G. (2003). Effectiveness of sensory and motor rehabilitation of the upper limb following the principles of neuroplasticity: patients stable poststroke. *Neurorehabilitation and neural repair*, 17(3), 176-191.

Caldwell, L. L., & Gilbert, A. A. (2009). Leisure, health, and disability: A review and discussion. *Canadian Journal of Community Mental Health*, 9(2), 111-122.

Calley, A., Williams, S., Reid, S., Blair, E., Valentine, J., Girdler, S., & Elliott, C. (2012). A comparison of activity, participation and quality of life in children with and without spastic diplegia cerebral palsy. *Disability and rehabilitation*, 34(15), 1306-1310.

Carda, S., Bertoni, M., Zerbinati, P., Rossini, M., Magoni, L., & Molteni, F. (2009). Gait changes after tendon functional surgery for equinovarus foot in patients with stroke: assessment of temporo-spatial, kinetic, and kinematic parameters in 177 patients. *American journal of physical medicine & rehabilitation*, 88(4), 292-301.

Carlson, W. E., Vaughan, C. L., Damiano, D. L., & Abel, M. F. (1997). Orthotic Management of Gait in Spastic Diplegia1. *American journal of physical medicine & rehabilitation*, 76(3), 219-225.

Carlsöö, S., Dahlöf, A. G., & Holm, J. (1974). Kinetic analysis of the gait in patients with hemiparesis and in patients with intermittent claudication. *Scandinavian journal of rehabilitation medicine*, 6(4), 166.

Carpinella, I., Cattaneo, D., Bertoni, R., & Ferrarin, M. (2012). Robot training of upper limb in multiple sclerosis: comparing protocols with or without manipulative task components. *Neural Systems and Rehabilitation Engineering*, IEEE Transactions on, 20(3), 351-360.

Cavagna, G. A., Franzetti, P., & Fuchimoto, T. (1983). The mechanics of walking in children. *The Journal of physiology*, *343*(1), 323-339.

Centers for Disease Control and Prevention (CDC). (2004). Economic costs associated with mental retardation, cerebral palsy, hearing loss, and vision impairment--United States, 2003. *MMWR. Morbidity and mortality weekly report*, 53(3), 57.

Centers for Disease Control and Prevention (CDC). (2015). *Data & Statistics for Cerebral Palsy*. Retrieved from http://www.cdc.gov/ncbddd/cp/data.html

Chamorro, C., Armijo-Olivo, S., De la Fuente, C., Fuentes, J., & Chirosa, L. J. (2017). Absolute reliability and concurrent validity of hand held dynamometry and isokinetic dynamometry in the hip, knee and ankle joint: systematic review and meta-analysis. *Open Medicine*, 12(1), 359-375.

Charles, J. R., Wolf, S. L., Schneider, J. A., & Gordon, A. M. (2006). Efficacy of a child-friendly form of constraint-induced movement therapy in hemiplegic cerebral palsy: a randomized control trial. *Developmental Medicine & Child Neurology*, *48*(08), 635-642.

Chen, C. P., Tang, S. F., Hsu, C. C., Chen, R. L., Hsu, R. C., Wu, C. W., & Chen, M. J. (2009). A novel approach to sonographic examination in a patient with a calf muscle tear: a case report. *Journal of medical case reports*, 3(1), 7291.

Chen, C. Shen, I., Chen, C., Wu, C., Liu, W., et al. (2013). “Validity, responsiveness, minimal detectable change, and minimal clinically important change of pediatric balance scale in children with cerebral palsy.” *Res Dev Disabil*, 34:916-922.

Chen, G., Patten, C., Kothari, D. H., & Zajac, F. E. (2005). Gait differences between individuals with post-stroke hemiparesis and non-disabled controls at matched speeds. *Gait & posture*, 22(1), 51-56.

Chen, R., Cohen, L., Hallett, M. (2002b). Nervous system reorganization following injury. *Neuroscience*, 111: 761–73.

Chiarello, L. A., Palisano, R. J., Bartlett, D. J., & McCoy, S. W. (2011). A multivariate model of determinants of change in gross-motor abilities and engagement in self-care and play of young children with cerebral palsy. *Physical & occupational therapy in pediatrics*, 31(2), 150-168.

Cimolin, V., Galli, M., Tenore, N., Albertini, G., & Crivellini, M. (2007). Gait strategy of uninvolved limb in children with spastic hemiplegia. *Europa medicophysica*, 43(3), 303-310.

Cioi, D., Kale, A., Burdea, G., Engsberg, J., Janes, W., & Ross, S. (2011, June). Ankle control and strength training for children with cerebral palsy using the Rutgers Ankle

CP. In *Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on* (pp. 1-6). IEEE.

Colombo, R., Pisano, F., Mazzone, A., Delconte, C., Micera, S., Carrozza, M. C., Dario, P. & Minuco, G. (2007). Design strategies to improve patient motivation during robot-aided rehabilitation. *Journal of neuroengineering and rehabilitation*, 4(1), 3.

Coq, J. O., & Xerri, C. (2001). Sensorimotor experience modulates age-dependent alterations of the forepaw representation in the rat primary somatosensory cortex. *Neuroscience*, 104, 705–715.

Cordo, P., Lutsep, H., Cordo, L., Wright, W. G., Cacciatore, T., & Skoss, R. (2009). Assisted movement with enhanced sensation (AMES): coupling motor and sensory to remediate motor deficits in chronic stroke patients. *Neurorehabilitation and neural repair*, 23(1), 67-77.

Cortes, M., Elder, J., Rykman, A., Murray, L., Avedissian, M., Stampa, A., et al. (2013). Improved motor performance in chronic spinal cord injury following upper-limb robotic training. *NeuroRehabilitation*, 33(1), 57-65.

Cote, K. P., Brunet, M. E., II, B. M. G., & Shultz, S. J. (2005). Effects of pronated and supinated foot postures on static and dynamic postural stability. *Journal of athletic training*, 40(1), 41.

Cramer, S.C. (2011). Harnessing neuroplasticity for clinical applications. *Brain*, 134(Pt 6):1591-609. doi: 10.1093/brain/awr039. Epub 2011 Apr 10.

Crompton, J., Galea, M. P., & Phillips, B. (2007). Hand-held dynamometry for muscle strength measurement in children with cerebral palsy. *Developmental Medicine & Child Neurology*, 49(2), 106-111.

da Matta, T. T., & de Oliveira, L. F. (2012). Reliability of the rectus femoris muscle cross-sectional area measurements by ultrasonography. *Clinical physiology and functional imaging*, 32(3), 221-226.

Dallmeijer, A. J., Baker, R., Dodd, K. J., & Taylor, N. F. (2011). Association between isometric muscle strength and gait joint kinetics in adolescents and young adults with cerebral palsy. *Gait & posture*, 33(3), 326-332.

Daly, J. J., Hogan, N., Perepezko, E. M., Krebs, H. I., Rogers, J. M., Goyal, K. S., et al. (2005). Response to upper-limb robotics and functional neuromuscular stimulation following stroke. *Journal of rehabilitation research and development*, 42(6), 723.

Damiano, D. L. (2006). Activity, activity, activity: rethinking our physical therapy approach to cerebral palsy. *Physical therapy*, 86(11), 1534-1540.

Damiano, D. L. (2009). Rehabilitative therapies in cerebral palsy: the good, the not as good, and the possible. *Journal of child neurology*, 24(9), 1200-1204.

Damiano, D. L., & Abel, M. F. (1998). Functional outcomes of strength training in spastic cerebral palsy. *Archives of physical medicine and rehabilitation,* 79(2), 119-125.

Damiano, D. L., Kelly, L. E., & Vaughn, C. L. (1995). Effects of quadriceps femoris muscle strengthening on crouch gait in children with spastic diplegia. *Physical therapy*, 75(8), 658-667.

Damiano, D. L., Martellotta, T. L., Sullivan, D. J., Granata, K. P., & Abel, M. F. (2000). Muscle force production and functional performance in spastic cerebral palsy: relationship of cocontraction. *Archives of Physical Medicine and Rehabilitation*, 81(7), 895-900.

Damiano, D. L., Vaughan, C. L., & Abel, M. E. (1995). Muscle response to heavy resistance exercise in children with spastic cerebral palsy. *Developmental Medicine & Child Neurology*, 37(8), 731-739.

Demura, T., Demura, S. I., Uchiyama, M., & Sugiura, H. (2014). Examination of factors affecting gait properties in healthy older adults: focusing on knee extension strength, visual acuity, and knee joint pain. *Journal of Geriatric Physical Therapy*, 37(2), 52-57.

Den Otter, A. R., Geurts, A. C. H., Mulder, T. H., & Duysens, J. (2007). Abnormalities in the temporal patterning of lower extremity muscle activity in hemiparetic gait. *Gait & posture*, 25(3), 342-352.

Desrosiers, J., Rochette, A., et al. (2003). "Comparison of two functional independence scales with a participation measure in post-stroke rehabilitation." *Arch Gerontol Geriatr*, 37(2): 157-172.

Deutsch, J. E., Latonio, J., Burdea, G. C., & Boian, R. (2001a). Post-stroke rehabilitation with the Rutgers Ankle System: a case study. *Presence: Teleoperators and Virtual Environments*, 10(4), 416-430.

Deutsch, J. E., Latonio, J., Burdea, G., & Boian, R. (2001b, July). Rehabilitation of musculoskeletal injuries using the Rutgers ankle haptic interface: three case reports. *In Proceedings of Eurohaptics* (pp. 11-16).

Deutsch, J. E., Lewis, J., & Burdea, G. (2007). Technical and patient performance using a virtual reality-integrated telerehabilitation system: preliminary finding. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, *15*(1), 30-35.

Deutsch, J. E., Paserchia, C., Vecchione, C., Mirelman, A., Lewis, J. A., Boian, R., & Burdea, G. (2004). Improved gait and elevation speed of individuals post-stroke after lower extremity training in virtual environment. *Journal of Neurologic Physical Therapy*, 28(4), 185-186.

Devita, P. A. U. L., & Skelly, W. A. (1992). Effect of landing stiffness on joint kinetics and energetics in the lower extremity. *Med Sci Sports Exerc*, 24(1), 108-115.

Diaz, I., Gil, J. J., & Sánchez, E. (2011). Lower-limb robotic rehabilitation: literature review and challenges. *Journal of Robotics*, 2011.

Dini, P. D., & David, A. C. (2009). Repeatability of spatiotemporal gait parameters: comparison between normal children and children with hemiplegic spastic cerebral palsy. *Brazilian Journal of Physical Therapy*, 13(3), 215-222.

DiStefano, L. J., Padua, D. A., Brown, C. N., & Guskiewicz, K. M. (2008). Lower extremity kinematics and ground reaction forces after prophylactic lace-up ankle bracing. *Journal of athletic training*, 43(3), 234.

Dodd, K. J., Taylor, N. F., & Graham, H. K. (2003). A randomized clinical trial of strength training in young people with cerebral palsy. *Developmental medicine and child neurology*, 45(10), 652-657.

Dong, Q., & Fessell, D. P. (2009). Achilles tendon ultrasound technique. *American journal of roentgenology*, 193(3), W173-W173.

Donkervoort, M., Roebroeck, M., Wiegerink, D., Van der Heijden-Maessen, H., Stam, H., & Transition Research Group South West Netherlands. (2007). Determinants of functioning of adolescents and young adults with cerebral palsy. *Disability and rehabilitation*, 29(6), 453-463.

Dyball, K. M., Taylor, N. F., & Dodd, K. J. (2011). Retest reliability of measuring hip extensor muscle strength in different testing positions in young people with cerebral palsy. *BMC pediatrics*, 11(1), 42.

Eek, M. N., & Beckung, E. (2008). Walking ability is related to muscle strength in children with cerebral palsy. *Gait & posture*, 28(3), 366-371.

Eek, M. N., Tranberg, R., & Beckung, E. (2011). Muscle strength and kinetic gait pattern in children with bilateral spastic CP. *Gait & posture*, 33(3), 333-337.

Effgen, S. K. (2012). Meeting the physical therapy needs of children. FA Davis.

Elbert, T., Pantev, C., Wienbruch, C., Rockstroh, B., Taub, E. (1995). Increased cortical representation of the fingers of the left hand in string players. *Science*, 13;270(5234):305-7.

Elder, G. C., Kirk, J., Stewart, G., Cook, K., Weir, D., Marshall, A., & Leahey, L. (2003). Contributing factors to muscle weakness in children with cerebral palsy. *Developmental medicine and child neurology*, 45(8), 542-550.

Ema, R., Akagi, R., Wakahara, T., & Kawakami, Y. (2016). Training-induced changes in architecture of human skeletal muscles: Current evidence and unresolved issues. *The Journal of Physical Fitness and Sports Medicine*, 5(1), 37-46.

Emmert, K., Kopel, R., Koush, Y., Maire, R., Senn, P., Van De Ville, D., & Haller, S. (2017). Continuous vs. intermittent neurofeedback to regulate auditory cortex activity of tinnitus patients using real-time fMRI-A pilot study. *NeuroImage: Clinical*, 14, 97-104.

Eng, J. J., & Winter, D. A. (1995). Kinetic analysis of the lower limbs during walking: what information can be gained from a three-dimensional model?. *Journal of biomechanics*, 28(6), 753-758.

Engsberg, J. R., Ross, S. A., & Collins, D. R. (2006). Increasing ankle strength to improve gait and function in children with cerebral palsy: a pilot study. *Pediatric Physical Therapy*, 18(4), 266-275.

Engsberg, J. R., Ross, S. A., Olree, K. S., & Park, T. S. (2000). Ankle spasticity and strength in children with spastic diplegic cerebral palsy. *Developmental medicine and child neurology*, 42(1), 42-47.

Enoka, R. M. (2002). *Neuromechanics of human movement*. Human kinetics. 3rd ed. Champaign, IL: Human Kinetics.

Esliger, D. W., & Tremblay, M. S. (2006). Technical reliability assessment of three accelerometer models in a mechanical setup. *Medicine and science in sports and exercise*, 38(12), 2173-2181.

Fasano, V. A., Broggi, G., Barolat-Romana, G., & Sguazzi, A. (1978). Surgical treatment of spasticity in cerebral palsy. *Pediatric Neurosurgery*, 4(5), 289-305.

Fasoli, S. E., Fragala-Pinkham, M., Hughes, R., Hogan, N., Krebs, H. I., & Stein, J. (2008). Upper limb robotic therapy for children with hemiplegia. *American Journal of Physical Medicine & Rehabilitation*, 87(11), 929-936.

Fasoli, S. E., Fragala-Pinkham, M., Hughes, R., Krebs, H. I., Hogan, N., & Stein, J. (2008). Robotic therapy and botulinum toxin type A: A novel intervention approach for cerebral palsy. *American Journal of Physical Medicine & Rehabilitation*, 87(12), 1022-1026.

Fasoli, S. E., Krebs, H. I., Stein, J., Frontera, W. R., & Hogan, N. (2003). Effects of robotic therapy on motor impairment and recovery in chronic stroke. *Archives of physical medicine and rehabilitation*, *84*(4), 477-482.

Fasoli, S. E., Ladenheim, B., Mast, J., & Krebs, H. I. (2012). New horizons for robot-assisted therapy in pediatrics. *American Journal of Physical Medicine & Rehabilitation*, *91*(11), S280-S289.

Ferris, D. P., & Farley, C. T. (1997). Interaction of leg stiffness and surface stiffness during human hopping. *Journal of applied physiology*, 82(1), 15-22.

Ferris, D. P., Louie, M., & Farley, C. T. (1998). Running in the real world: adjusting leg stiffness for different surfaces. Proceedings of the Royal Society of London. *Series B: Biological Sciences*, 265(1400), 989-994.

Feys, H. M., De Weerdt, W. J., Selz, B. E., Steck, G. A. C., Spichiger, R., Vereeck, L. E., and et al. (1998). Effect of a therapeutic intervention for the hemiplegic upper limb in the acute phase after stroke a single-blind, randomized, controlled multicenter trial. *Stroke*, 29(4), 785-792.

Fifkova, E. (1969). The effect of monocular deprivation on the synaptic contacts of the visual cortex. *Journal of Neurobiology,* 1, 285–294.

Finch, E., Brooks, D., Stratford, P., Mayo, N. (2002). *Physical rehabilitation outcome measures: a guide to enhanced clinical decision making.* 2nd ed. Hamilton, Ontario: BC Decker Inc.

Fisher, B.E., & Sullivan, K.J. (2001). Activity-dependent factors affecting post stroke functional outcomes. *Top Stroke Rehabil*, 8(3):31-44.

Flansbjer, U. B., Downham, D., & Lexell, J. (2006). Knee muscle strength, gait performance, and perceived participation after stroke. *Archives of physical medicine and rehabilitation*, 87(7), 974-980.

Flett, P. J. (2003). Rehabilitation of spasticity and related problems in childhood cerebral palsy. *Journal of Paediatrics and child health*, 39(1), 6-14.

Fluet, G. G., et al. (2010). "Interfacing a haptic robotic system with complex virtual environments to treat impaired upper extremity motor function in children with cerebral palsy." *Dev Neurorehabil*, 13(5): 335-345.

Fonseca, S. T., Holt, K. G., Fetters, L., & Saltzman, E. (2004). Dynamic resources used in ambulation by children with spastic hemiplegic cerebral palsy: relationship to kinematics, energetics, and asymmetries. *Physical Therapy*, 84(4), 344-354.

Forrester, L. W., Roy, A., Goodman, R. N., Rietschel, J., Barton, J. E., Krebs, H. I., & Macko, R. F. (2013). Clinical application of a modular ankle robot for stroke rehabilitation. *NeuroRehabilitation*, 33(1), 85-97.

Forrester, L. W., Roy, A., Goodman, R. N., Rietschel, J., Barton, J. E., Krebs, H. I., & Macko, R. F. (2013). Clinical application of a modular ankle robot for stroke rehabilitation. *NeuroRehabilitation*, 33(1), 85-97.

Forrester, L. W., Roy, A., Krebs, H. I., & Macko, R. F. (2011). Ankle training with a robotic device improves hemiparetic gait after a stroke. *Neurorehabilitation and neural repair*, 25(4), 369-377.

Forrester, L. W., Roy, A., Krebs, H. I., & Macko, R. F. (2011). Ankle training with a robotic device improves hemiparetic gait after a stroke. *Neurorehabilitation and neural repair*, 25(4), 369-377.

Forrester, L. W., Roy, A., Krywonis, A., Kehs, G., Krebs, H. I., & Macko, R. F. (2014). Modular ankle robotics training in early subacute stroke a randomized controlled pilot study. *Neurorehabilitation and neural repair*, 1545968314521004.

Forsyth, R., & Jarvis, S. (2002). Participation in childhood. *Child: care, health and development*, 28(4), 277-279.

Fosang, A. L., Galea, M. P., et al. (2003). "Measures of muscle and joint performance in the lower limb of children with cerebral palsy." *Dev Med Child Neurol*, 45(10): 664-670.

Fougeyrollas, P., Noreau, L., Bergeron, H., Cloutier, R., Dion, S. A., & St-Michel, G. (1998). Social consequences of long term impairments and disabilities: conceptual approach and assessment of handicap. *International Journal of Rehabilitation Research*, 21(2), 127-142.

Fowler, E. G., & Goldberg, E. J. (2009). The effect of lower extremity selective voluntary motor control on interjoint coordination during gait in children with spastic diplegic cerebral palsy. *Gait & posture*, 29(1), 102-107.

Fowler, E.G., Staudt, L.A., & Greenberg, M.B. (2010). Lower-extremity selective voluntary motor control in patients with spastic cerebral palsy: increased distal motor impairment. *Developmental medicine and child neurology*, 52(3):264–9.

Franjoine, M. R., Darr, N., Held, S. L., Kott, K., & Young, B. L. (2010). The performance of children developing typically on the pediatric balance scale. *Pediatric physical therapy*, 22(4), 350-359.

Franjoine, M. R., Gunther, J. S., & Taylor, M. J. (2003). Pediatric balance scale: a modified version of the berg balance scale for the school-age child with mild to moderate motor impairment. *Pediatric Physical Therapy*, 15(2), 114-128.

Frascarelli, F., Masia, L., Di Rosa, G., Cappa, P., Petrarca, M., Castelli, E., & Krebs, H. I. (2009). The impact of robotic rehabilitation in children with acquired or congenital movement disorders. *Eur J Phys Rehabil Med*, 45(1), 135-141.

Fukutani, A., & Kurihara, T. (2015). Tendon cross-sectional area is not associated with muscle volume. *Journal of applied biomechanics*, 31(3), 176-180.

Gage, J. R. (2004). A qualitative description of normal gait. *Clinics in developmental medicine*, 42-70.

Gage, J. R., (2004). *The treatment of gait problems in cerebral palsy*. Mac Keith Press, London.

Gage, J. R., Schwartz, M. H., Koop, S. E., & Novacheck, T. F. (Eds.). (2009). *The identification and treatment of gait problems in cerebral palsy* (Vol. 4). John Wiley & Sons.

Gajdosik, R.L., & Bohannon, R.W. (1987). Clinical measurement of range of motion. Review of goniometry emphasizing reliability and validity. *Phys Ther*, 67(12):1867-72.

Gardner, W., Karnosh, L., McClure, C., Gardner, A. (1955). Residual function following hemispherectomy for tumor and for infantile hemiplegia. *Brain*, 78: 487–502.

Gauthier, L.V., Taub, E., Perkins, C., Ortmann, M., Mark, V.W., Uswatte, G. (2008). Remodeling the brain: plastic structural brain changes produced by different motor therapies after stroke. *Stroke*, 39: 1520–5.

Gilbertson, T. J. (2016). *NeuroGame Therapy for the Improvement of Ankle Control in Ambulatory Children with Cerebral Palsy* (Doctoral dissertation).

Gilliaux, M., et al. (2015). "Upper limb robot-assisted therapy in cerebral palsy: a single-blind randomized controlled trial." *Neurorehabil Neural Repair*, 29(2): 183-192.

Gilmore, J.H., Lin, W., Prasatwa, M.W., et al. (2007). Regional gray matter growth, sexual dimorphism, and cerebral asymmetry in the neonatal brain. *Journal of Neuroscience*, 27(6):1255-1260.

Girone, M., Burdea, G., Bouzit, M., Popescu, V., & Deutsch, J. E. (2000). Orthopedic rehabilitation using the" Rutgers ankle" interface. *Studies in health technology and informatics*, 89-95.

Goodman, R. N., Rietschel, J. C., Roy, A., Balasubramanian, S., Forrester, L. W., Bever, C. T., & Krebs, H. I. (2014, August). Ankle robotics training with concurrent physiological monitoring in multiple sclerosis: A case report. *In Biomedical Robotics and Biomechatronics (2014 5th IEEE RAS & EMBS International Conference on* (pp. 393-397). IEEE.

Gormley, M.E. Jr. (2001). Treatment of neuromuscular and musculoskeletal problems in cerebral palsy. *Developmental Neurorehabilitation*, 4(1), 5-16.

Gracies, J.M., Burke, K., Clegg, N.J., Browne, R., Rushing, C., Fehlings, D., Matthews, D., Tilton, A., Delgado, M.R. (2010). Reliability of the Tardieu Scale for assessing spasticity in children with cerebral palsy. *Arch Phys Med Rehabil*, 91(3):421-8.

Gracies, J.M., Lugassy, M., Weisz, D.J., Vecchio, M., Flanagan, S., and Simpson, D.M. (2009). Botulinum toxin dilution and endplate targeting in spasticity: a double-blind controlled study. *Arch Phys Med Rehab*, 90: 9–16.

Gracies, J.M., Marosszeky, J.E., Renton, R., Sandanam, J., Gandevia, S.C., and Burke, D. (2000). Short-term effects of dynamic Lycra splints on upper limb in hemiplegic patients. *Arch Phys Med Rehabil*, 81: 1547–1555.

Greene, T. A., & Roland, G. C. (1989). A comparative isokinetic evaluation of a functional ankle orthosis on talocalcaneal function. *Journal of Orthopaedic & Sports Physical Therapy*, 11(6), 245-252.

Greene, T. A., & Wight, C. R. (1990). A comparative support evaluation of three ankle orthoses before, during, and after exercise. *Journal of Orthopaedic & Sports Physical Therapy*, 11(10), 453-466.

Greenough, W. T., McDonald, J. W., Parnisari, R. M., & Camel, J. E. (1986). Environmental conditions modulate degeneration and new dendrite growth in cerebellum of senescent rats. *Brain Research*, 380, 136–143.

Gross, M. T., Ballard, C. L., Mears, H. G., & Watkins, E. J. (1992). Comparison of Donjoy® ankle ligament protector and Aircast® sport-stirrup™ orthoses in restricting foot and ankle motion before and after exercise. *Journal of Orthopaedic & Sports Physical Therapy*, 16(2), 60-67.

Haff, G. G., & Triplett, N. T. (Eds.). (2015). *Essentials of strength training and conditioning 4th edition (pp. 94).* Human kinetics.

Hägglund, G., & Wagner, P. (2011). Spasticity of the gastrosoleus muscle is related to the development of reduced passive dorsiflexion of the ankle in children with cerebral palsy: a registry analysis of 2,796 examinations in 355 children. *Acta orthopaedica*, 82(6), 744-748.

Hamilton, N. P. (2011). *Kinesiology: scientific basis of human motion*. Brown & Benchmark.

Hansen, P., Aagaard, P., Kjaer, M., Larsson, B., & Magnusson, S. P. (2003). Effect of habitual running on human Achilles tendon load-deformation properties and cross-sectional area. *Journal of applied physiology,* 95(6), 2375-2380.

Harris, S. (1991). Efficacy of early intervention in pediatric rehabilitation. *Phys Med Rehabil Clin N Am*, 2:725.

Haugh, A.B., Pandyan, A.D., Johnson, G.R. (2006). A systematic review of the Tardieu Scale for the measurement of spasticity. *Disab Rehabil*, 28:899–907.

Healthy People 2020. (2015). Retrieved from http://www.healthypeople.gov/2020/default.aspx.

Henderson, N. K., White, C. P., & Eisman, J. A. (1998). The roles of exercise and fall risk reduction in the prevention of osteoporosis. *Endocrinology and metabolism clinics of North America*, 27(2), 369-387.

Henderson, R. C., Lark, R. K., Gurka, M. J., Worley, G., Fung, E. B., Conaway, M., Stallings, V.A. & Stevenson, R. D. (2002). Bone density and metabolism in children and adolescents with moderate to severe cerebral palsy. *Pediatrics*, 110(1), e5-e5.

Hesse, S., Schulte-Tigges, G., Konrad, M., Bardeleben, A., & Werner, C. (2003). Robot-assisted arm trainer for the passive and active practice of bilateral forearm and wrist movements in hemiparetic subjects1. *Archives of physical medicine and rehabilitation*, 84(6), 915-920.

Higginson, J. S., Zajac, F. E., Neptune, R. R., Kautz, S. A., & Delp, S. L. (2006). Muscle contributions to support during gait in an individual with post-stroke hemiparesis. *Journal of Biomechanics*, 39(10), 1769-1777.

Himmelmann, K., Beckung, E., Hagberg, G., & Uvebrant, P. (2006). Gross and fine motor function and accompanying impairments in cerebral palsy. *Developmental Medicine & Child Neurology*, 48(6), 417-423.

Himmelmann, K., Hagberg, G., Beckung, E., Hagberg, B., Uvebrant, P. (2005). The changing panorama of cerebral palsy in Sweden. IX. Prevalence and origin in the birth-year period 1995–1998. *Acta Paediatr*, 94: 287–294.

Homma, K., & Usuba, M. (2007, June). Development of ankle dorsiflexion/ plantarflexion exercise device with passive mechanical joint. In*Rehabilitation Robotics, 2007. ICORR 2007. IEEE 10th International Conference on* (pp. 292-297). IEEE.

Hopper, D. M., McNair, P., & Elliott, B. C. (1999). Landing in netball: effects of taping and bracing the ankle. *British journal of sports medicine*, 33(6), 409-413.

Horlings, C. G., Van Engelen, B. G., Allum, J. H., & Bloem, B. R. (2008). A weak balance: the contribution of muscle weakness to postural instability and falls. *Nature Clinical Practice Neurology*, 4(9), 504-515.

Hornby, T. G., Zemon, D. H., & Campbell, D. (2005). Robotic-assisted, body-weight–supported treadmill training in individuals following motor incomplete spinal cord injury. *Physical therapy*, 85(1), 52-66.

Howle, J. M. (2002). Neuro-developmental treatment approach: theoretical foundations and principles of clinical practice. *NeuroDevelopmental Treatment*. http://www.ninds.nih.gov/disorders/cerebral_palsy/detail_cerebral_palsy.htm

Hrysomallis, C. (2007). Relationship between balance ability, training and sports injury risk. *Sports Medicine*, 37(6), 547-556.

Hsu, A. L., Tang, P. F., & Jan, M. H. (2003). Analysis of impairments influencing gait velocity and asymmetry of hemiplegic patients after mild to moderate stroke. *Archives of physical medicine and rehabilitation*, 84(8), 1185-1193.

Hubel, D. H., & Wiesel, T. N. (1965). Binocular interaction in striate cortex of kittens reared with artificial squint. *Journal of Neurophysiology*, 28, 1041–1059.

Huber, M., Rabin, B., Docan, C., Burdea, G. C., AbdelBaky, M., & Golomb, M. R. (2010). Feasibility of modified remotely monitored in-home gaming technology for improving hand function in adolescents with cerebral palsy. *IEEE Transactions on information technology in biomedicine*, 14(2), 526-534.

Hughes, L. Y., & Stetts, D. M. (1983). A comparison of ankle taping and a semirigid support. *Physician Sportsmed*, 11(4), 99-103.

Huijing, P. A., Bénard, M. R., Harlaar, J., Jaspers, R. T., & Becher, J. G. (2013). Movement within foot and ankle joint in children with spastic cerebral palsy: a 3-dimensional ultrasound analysis of medial gastrocnemius length with correction for effects of foot deformation. *BMC musculoskeletal disorders*, 14(1), 365.

Jago, R., Anderson, C. B., Baranowski, T., & Watson, K. (2005). Adolescent patterns of physical activity: Differences by gender, day, and time of day. *American journal of preventive medicine*, 28(5), 447-452.

Jahnsen, R., Villien, L., Aamodt, G., Stanghelle, J., & Holm, I. (2004). Musculoskeletal pain in adults with cerebral palsy compared with the general population. *Journal of Rehabilitation Medicine*, 36(2), 78-84.

Jahnsen, R., Villien, L., Egeland, T., & Stanghelle, J. K. (2004). Locomotion skills in adults with cerebral palsy. *Clinical rehabilitation*, 18(3), 309-316.

Jahnsen, R., Villien, L., Stanghelle, J. K., & Holm, I. (2003). Fatigue in adults with cerebral palsy in Norway compared with the general population. *Developmental Medicine & Child Neurology*, 45(05), 296-303.

Janssen, I., Baumgartner, R. N., Ross, R., Rosenberg, I. H., & Roubenoff, R. (2004). Skeletal muscle cutpoints associated with elevated physical disability risk in older men and women. *American journal of epidemiology*, 159(4), 413-421.

Jarvis, S., & Hey, E. (1984). Measuring disability and handicap due to cerebral palsy. *The epidemiology of the cerebral palsies. Clinics in Developmental Medicine*, (87), 35-45.

Jette, A. M. (2006). Toward a common language for function, disability, and health. *Physical therapy*, 86(5), 726-734.

Johnson, K. A., Hartwell, K., LeMatty, T., Borckardt, J., Morgan, P. S., Govindarajan, K., Brady, K. and George, M. S. (2012). Intermittent “Real-time” fMRI feedback is superior to continuous presentation for a motor imagery task: a pilot study. *Journal of Neuroimaging*, 22(1), 58-66.

Johnson, R. E., Veale, J. R., & McCarthy, G. J. (1994). Comparative study of ankle support devices. *Journal of the American Podiatric Medical Association*, 84(3), 107-114.

Johnston, M.V. (2003). Brain plasticity in paediatric neurology. *Eur J Paediatr Neurol*, 7(3):105-13.

Johnston, M.V., Nishimura, A., Harum, K., Pekar, J., Blue, M.E. (2001). Sculpting the developing brain. *Adv Pediatr*, 48:1-38.

Jones, T. A., Chu, C. J., Grande, L. A., & Gregory, A. D. (1999). Motor skills training enhances lesion-induced structural plasticity in the motor cortex of adult rats. *Journal of Neuroscience*, 19, 10153–10163.

Jung, B. C., Diaz, J., & Macko, R. F. (2014). Increased reward in ankle robotics training enhances motor control and cortical efficiency in stroke. *Journal of rehabilitation research and development*, 51(2), 213.

Kahn, L. E., Averbuch, M., Rymer, W. Z., & Reinkensmeyer, D. J. (2001). Comparison of robot-assisted reaching to free reaching in promoting recovery from chronic stroke. In *Proceedings of the International Conference on Rehabilitation Robotics* (pp. 39-44).

Kawakami, Y., Abe, T., Kuno, S. Y., & Fukunaga, T. (1995). Training-induced changes in muscle architecture and specific tension. *European journal of applied physiology and occupational physiology*, 72(1-2), 37-43.

Kelso, J. S., & Tuller, B. (1984). *A dynamical basis for action systems*. In Handbook of cognitive neuroscience (pp. 321-356). Springer US.

Kelso, J. S., Holt, K. G., Kugler, P. N., & Turvey, M. T. (1980). 2 On the Concept of Coordinative Structures as Dissipative Structures: II. Empirical Lines of Convergence. *Advances in Psychology*, 1, 49-70.

Kerr, C., McDowell, B., & McDonough, S. (2007). The relationship between gross motor function and participation restriction in children with cerebral palsy: an exploratory analysis. *Child: care, health and development*, 33(1), 22-27.

Kerr, C., Parkes, J., Stevenson, M., Cosgrove, A. P., & McDowell, B. C. (2008). Energy efficiency in gait, activity, participation, and health status in children with cerebral palsy. *Developmental Medicine & Child Neurology*, 50(3), 204-210.

Khamis, S., & Yizhar, Z. (2007). Effect of feet hyperpronation on pelvic alignment in a standing position. *Gait & posture*, 25(1), 127-134.

Kimura, I. F., Nawoczenski, D. A., Epler, M., & Owen, M. G. (1987). Effect of the AirStirrup in controlling ankle inversion stress. *Journal of Orthopaedic & Sports Physical Therapy*, 9(5), 190-193.

King, G., Law, M., Hanna, S., King, S., Hurley, P., Rosenbaum, P., Kertoy, M., & Petrenchik, T. (2006). Predictors of the leisure and recreation participation of children with physical disabilities: a structural equation modeling analysis. *Children's Health Care*, 35(3), 209-234.

King, G., McDougall, J., Dewit, D., Petrenchik, T., Hurley, P., & Law, M. (2009). Predictors of change over time in the activity participation of children and youth with physical disabilities. *Children’s Health Care*, 38, 321-351.

Klaas, S. J., Kelly, E. H., Gorzkowski, J., Homko, E., & Vogel, L. C. (2010). Assessing patterns of participation and enjoyment in children with spinal cord injury. *Developmental Medicine and Child Neurology*, 52(5), 468-474.

Kleim, J. A., & Jones, T. A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *Journal of speech, language, and hearing research*, 51(1), S225-S239.

Kleim, J. A., Barbay, S., Cooper, N. R., Hogg, T. M., Reidel, C. N., Remple, M. S., & Nudo, R. J. (2002). Motor learning-dependent synaptogenesis is localized to functionally reorganized motor cortex. *Neurobiology of learning and memory*, 77(1), 63-77.

Kleim, J. A., Cooper, N. R., & VandenBerg, P. M. (2002). Exercise induces angiogenesis but does not alter movement representations within rat motor cortex. *Brain research*, 934(1), 1-6.

Kleim, J.A., and Jones, T.A. (2008). Principles of experience-dependent neural plasticity: implications for rehabilitation after brain damage. *J Speech Lang Hear Res*, 51(1):S225-39. doi: 10.1044/1092-4388(2008/018).

Kleim, J.A., Hogg, T.M., VandenBerg, P.M., Cooper, N.R., Bruneau, R., Remple, M. (2004). Cortical synaptogenesis and motor map reorganization occur during late, but not early, phase of motor skill learning. *J Neurosci*, 24(3):628-33.

Krakauer, J. W. (2006). Motor learning: its relevance to stroke recovery and neurorehabilitation. *Current opinion in neurology*, *19*(1), 84-90.

Kramer, J. F., & MacPhail, H. A. (1994). Relationships among measures of walking efficiency, gross motor ability, and isokinetic strength in adolescents with cerebral palsy. *Pediatric Physical Therapy*, 6 (1), 3-8.

Krebs, H. I., Fasoli, S. E., Dipietro, L., Fragala-Pinkham, M., Hughes, R., Stein, J., & Hogan, N. (2012). Motor learning characterizes habilitation of children with hemiplegic cerebral palsy. *Neurorehabilitation and neural repair*, 26(7), 855-860.

Krebs, H. I., Hogan, N., Aisen, M. L., & Volpe, B. T. (1998). Robot-aided neurorehabilitation. Rehabilitation Engineering, IEEE Transactions on, 6(1), 75-87.

Krebs, H. I., Ladenheim, B., Hippolyte, C., Monterroso, L., & Mast, J. (2009). Robot-assisted task-specific training in cerebral palsy. *Developmental Medicine & Child Neurology*, 51(s4), 140-145.

Krebs, H. I., Michmizos, K. P., Monterosso, L., & Mast, J. (2016, June). Pediatric Anklebot: Pilot clinical trial. *In Biomedical Robotics and Biomechatronics (BioRob), 2016 6th IEEE International Conference on* (pp. 662-666). IEEE.

Krebs, H. I., Volpe, B. T., Aisen, M. L., & Hogan, N. (2000). Increasing productivity and quality of care: robot-aided neuro-rehabilitation. *Journal of rehabilitation research and development*, 37(6), 639-652.

Krebs, H., Rossi, S., Kim, S. J., Artemiadis, P. K., Williams, D., Castelli, E., & Cappa, P. (2011, June). Pediatric anklebot. *In Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on* (pp. 1-5). IEEE.

Krishnan, C., Kotsapouikis, D., Dhaher, Y. Y., & Rymer, W. Z. (2013). Reducing robotic guidance during robot-assisted gait training improves gait function: a case report on a stroke survivor. *Archives of physical medicine and rehabilitation*, 94(6), 1202-1206.

Kutner, N. G., Zhang, R., Butler, A. J., Wolf, S. L., & Alberts, J. L. (2010). Quality-of-life change associated with robotic-assisted therapy to improve hand motor function in patients with subacute stroke: a randomized clinical trial. *Physical therapy*, 90(4), 493-504.

Kwakkel, G., Kollen, B. J., & Krebs, H. I. (2008). Effects of robot-assisted therapy on upper limb recovery after stroke: a systematic review. *Neurorehabilitation and neural repair*, 22(2): 111–121.

Kwakkel, G., Kollen, B., & Lindeman, E. (2004). Understanding the pattern of functional recovery after stroke: facts and theories. *Restorative neurology and neuroscience*, 22(3-5), 281-300.

Ladenheim, B., Altenburger, P., Cardinal, R., Monterroso, L., Dierks, T., Mast, J., & Krebs, H. I. (2013). The effect of random or sequential presentation of targets during robot-assisted therapy on children. *NeuroRehabilitation*, *33*(1), 25-31.

Lairamore, C., Garrison, M. K., Bandy, W., & Zabel, R. (2011). Comparison of tibialis anterior muscle electromyography, ankle angle, and velocity when individuals post stroke walk with different orthoses. *Prosthetics and orthotics international*, 35(4), 402-410.

Lark, S. D., Buckley, J. G., Bennett, S., Jones, D., & Sargeant, A. J. (2003). Adequate joint stiffness is critical during the single support phase to control forward and downward body momentum. *Clin Biomech*, 18, 848-855.

Laughman, R. K., Carr, T. A., Chao, E. Y., Youdas, J. W., & Sim, F. H. (1980). Three-dimensional kinematics of the taped ankle before and after exercise. *The American journal of sports medicine,* 8(6), 425-431.

Law, M., Finkelman, S., Hurley, P., Rosenbaum, P., King, S., King, G., & Hanna, S. (2004). Participation of children with physical disabilities: relationships with diagnosis, physical function, and demographic variables. Scandinavian Journal of Occupational Therapy, 11(4), 156-162.

Law, M., King, G., King, S., Kertoy, M., Hurley, P., Rosenbaum, P., Young, N. & Hanna, S. (2006). Patterns of participation in recreational and leisure activities among children with complex physical disabilities. *Developmental medicine and child neurology*, 48(5), 337-342.

Lee, K. W., Kim, S. B., Lee, J. H., Lee, S. J., & Yoo, S. W. (2016). Effect of Upper Extremity Robot-Assisted Exercise on Spasticity in Stroke Patients. *Annals of rehabilitation medicine*, 40(6), 961-971.

Lee, T.D., & Genovese, E.D. (1988). Distribution of practice in motor skill acquisition: learning and performance effects reconsidered. *Res Q Exerc Sport*, 59: 277–287.

Lehmann, J. F., Condon, S. M., De Lateur, B. J., & Price, R. (1986). Gait abnormalities in peroneal nerve paralysis and their corrections by orthoses: a biomechanical study. *Archives of physical medicine and rehabilitation*, 67(6), 380-386.

Levy-Tzedek, S., Krebs, H. I., Shils, J. L., Apetauerova, D., & Arle, J. E. (2007). Parkinson's disease: a motor control study using a wrist robot. *Advanced Robotics*, 21(10), 1201-1213.

Li, Y., & Wright, D. L. (2000). An assessment of the attention demands during random- and blocked-practice schedules. *The Quarterly Journal of Experimental Psychology: Section A*, *53*(2), 591-606.

Lieber, R. L., & Friden, J. (2000). Functional and clinical significance of skeletal muscle architecture. *Muscle & nerve*, 23(11), 1647-1666.

Liptak, G. S. (2008). Health and well-being of adults with cerebral palsy. *Current opinion in Neurology*, 21(2), 136-142.

Lisman, J., & Spruston, N. (2005). Postsynaptic depolarization requirements for LTP and LTD: a critique of spike timing dependent plasticity. *Nature Neuroscience*, 8, 839–841.

Lo, A. C., Guarino, P. D., Richards, L. G., Haselkorn, J. K., Wittenberg, G. F., Federman, D. G., et al. (2010). Robot-assisted therapy for long-term upper-limb impairment after stroke. *New England Journal of Medicine*, *362*(19), 1772-1783.

Löfvenberg, R., & Karrholm, J. (1993). The influence of an ankle orthosis on the talar and calcaneal motions in chronic lateral instability of the ankle A stereophotogrammetric analysis. *The American journal of sports medicine*, 21(2), 224-230.

Low, N.L. (1980). A hypothesis why early intervention in cerebral palsy might be useful. *Brain Dev*, 2:133.

Lowing, K., Bexelius, A., Carlberg, E.B. (2010). Goal-directed functional therapy: a longitudinal study on gross motor function in children with cerebral palsy. *Disabil Rehabil*, 32(11):908-16.

Luke, L. M., Allred, R. P., & Jones, T. A. (2004). Unilateral ischemic sensorimotor cortical damage induces contralesional synaptogenesis and enhances skilled reaching with the ipsilateral forelimb in adult male rats. *Synapse*, 54, 187–199.

Lum, P. S., Burgar, C. G., & Shor, P. C. (2004). Evidence for improved muscle activation patterns after retraining of reaching movements with the MIME robotic system in subjects with post-stroke hemiparesis. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 12(2), 186-194.

Lum, P. S., Burgar, C. G., Shor, P. C., Majmundar, M., & Van der Loos, M. (2002). Robot-assisted movement training compared with conventional therapy techniques for the rehabilitation of upper-limb motor function after stroke. *Archives of physical medicine and rehabilitation*, 83(7), 952-959.

Lundkvist, J., Jarnlo, G.B., Gummesson, C., Nordmark, E. (2009). Longitudinal construct validity of the GMFM-88 total score and goal total score and the GMFM-66 score in a 5-year follow-up study. *Phys Ther*, 89(4):342-50.

Mack, R. P. (1982). Ankle injuries in athletics. Clinics in sports medicine, 1(1), 71-84.

MacKean, L. C., Bell, G., & Burnham, R. S. (1995). Prophylactic ankle bracing vs. taping: effects on functional performance in female basketball players. *Journal of Orthopaedic & Sports Physical Therapy*, 22(2), 77-81.

MacPhail, H. E., & Kramer, J. F. (1995). Effect of Isokinetic Strength-Training on Functional Ability And Walking Efficiency in Adolescents With Cerebral Palsy. *Developmental Medicine & Child Neurology*, 37(9), 763-775.

Maher, C. A., Williams, M. T., Olds, T., & Lane, A. E. (2007). Physical and sedentary activity in adolescents with cerebral palsy. *Developmental Medicine and Child Neurology*, 49(6), 450-457.

Majnemer, A. (2006). Assessment tools for cerebral palsy: new directions. *Future neurology*, 1 (6).

Majnemer, A., Shevell, M., Law, M., Birnbaum, R., Chilingaryan, G., Rosenbaum, P., & Poulin, C. (2008). Participation and enjoyment of leisure activities in school-aged children with cerebral palsy. *Developmental Medicine & Child Neurology*, 50(10), 751-758.

Maltais, D., Bar-Or, O. D. E. D., Galea, V., & Pierrynowski, M. I. C. H. A. E. L. (2001). Use of orthoses lowers the O (2) cost of walking in children with spastic cerebral palsy. *Medicine and science in sports and exercise*, 33(2), 320-325.

Matsuda, K., Ikeda, S., Nakahara, M., Ikeda, T., Okamoto, R., Kurosawa, K., & Horikawa, E. (2015). Factors affecting the coefficient of variation of stride time of the elderly without falling history: a prospective study. *Journal of physical therapy science*, 27(4), 1087-1090.

McBurney, H., Taylor, N. F., Dodd, K. J., & Graham, H. K. (2003). A qualitative analysis of the benefits of strength training for young people with cerebral palsy. *Developmental medicine and child neurology*, 45(10), 658-663.

McCaw, S. T., & Bates, B. T. (1991). Biomechanical implications of mild leg length inequality. *British journal of sports medicine*, 25(1), 10-13.

McCaw, S. T., & Cerullo, J. F. (1999). Prophylactic ankle stabilizers affect ankle joint kinematics during drop landings. *Medicine and science in sports and exercise*, 31(5), 702-707.

McClenaghan, B. A., Thombs, L., & Milner, M. (1992). Effects Of Seat-Surface Inclination On Postural Stability And Function Of The Upper Extremities Of Children With Cerebral Palsy. *Developmental medicine & child neurology*, 34(1), 40-48.

McGehrin, K., Roy, A., Goodman, R., Rietschel, J., Forrester, L., & Bever, C. (2012). Ankle Robotics Training in Sub-Acute Stroke Survivors: Concurrent within-Session

Changes in Ankle Motor Control and Brain Electrical Activity (P01. 175). *Neurology*, 78(1 Supplement), P01-175.

Mcnee, A. E., Gough, M., Morrissey, M. C., & Shortland, A. P. (2009). Increases in muscle volume after plantarflexor strength training in children with spastic cerebral palsy. *Developmental Medicine & Child Neurology*, 51(6), 429-435.

Mehrholz, J., Wagner, K., Meissner, D., Grundmann, K., Zange, C., Koch, R., et al. (2005). Reliability of the Modified Tardieu Scale and the Modified Ashworth Scale in adult patients with severe brain injury: a comparison study. *Clin Rehabil,* 19:751-9.

Mentiplay, B. F., Perraton, L. G., Bower, K. J., Adair, B., Pua, Y. H., Williams, G. P., McGaw, R. & Clark, R. A. (2015). Assessment of lower limb muscle strength and power using hand-held and fixed dynamometry: a reliability and validity study. *PloS one*, 10(10), e0140822.

Meyer-Heim, A., Ammann-Reiffer, C., Schmartz, A., Schaefer, J., Sennhauser, F. H., Heinen, F., et al. (2009). Improvement of walking abilities after robotic-assisted locomotion training in children with cerebral palsy. *Archives of disease in childhood*, 94(8), 615-620.

Meyer-Heim, A., Borggraefe, I., Ammann-Reiffer, C., Berweck, S., Sennhauser, F. H., Colombo, G., Knecht, B. & Heinen, F. (2007). Feasibility of robotic-assisted locomotor training in children with central gait impairment. *Developmental Medicine & Child Neurology*, 49(12), 900-906.

Michelsen, S. I., Flachs, E. M., Uldall, P., Eriksen, E. L., McManus, V., Parkes, J., Parkinson, K.N., Thyen, U., Arnaud, C., Beckung, E. & Dickinson, H. O. (2009). Frequency of participation of 8–12-year-old children with cerebral palsy: a multicentre cross-sectional European study. *European journal of paediatric neurology,* 13(2), 165-177.

Michelsen, S. I., Uldall, P., Kejs, A. M. T., & Madsen, M. (2005). Education and employment prospects in cerebral palsy. *Developmental Medicine & Child Neurology*, 47(8), 511-517.

Michelsen, S. I., Uldall, P., Madsen, M., & Hansen, T. (2006). Social integration of adults with cerebral palsy. *Developmental Medicine & Child Neurology*, 48(8), 643-649.

Michmizos, K. P., & Krebs, H. I. (2012). Serious games for the pediatric anklebot. *In Biomedical robotics and biomechatronics (BioRob),* 2012 4th IEEE RAS & EMBS international conference on (pp. 1710-1714). IEEE.

Michmizos, K. P., & Krebs, H. I. (2012, June). Assist-as-needed in lower extremity robotic therapy for children with cerebral palsy. *In Biomedical Robotics and Biomechatronics (BioRob),* 2012 4th IEEE RAS & EMBS International Conference on (pp. 1081-1086). IEEE.

Michmizos, K. P., & Krebs, H. I. (2012, June). Serious games for the pediatric anklebot. In *Biomedical Robotics and Biomechatronics (BioRob), 2012 4th IEEE RAS & EMBS International Conference on* (pp. 1710-1714). IEEE.

Michmizos, K., Rossi, S., Castelli, E., Cappa, P., & Krebs, H. (2015). Robot-Aided Neurorehabilitation: A Pediatric Robot for Ankle Rehabilitation. *IEEE*.

Miller, F. (2005). *Cerebral Palsy.* New York, NY: Springer.

Miltner, W. H., Bauder, H., Sommer, M., Dettmers, C., & Taub, E. (1999). Effects of constraint-induced movement therapy on patients with chronic motor deficits after stroke: a replication. *Stroke*, 30(3), 586-592

Mirbagheri, M. M., Ness, L. L., Patel, C., Quiney, K., & Rymer, W. Z. (2011, June). The effects of robotic-assisted locomotor training on spasticity and volitional control. *In Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on* (pp. 1-4). IEEE.

Mirelman, A., Bonato, P., & Deutsch, J. E. (2009). Effects of training with a robot-virtual reality system compared with a robot alone on the gait of individuals after stroke. *Stroke*, 40(1), 169-174.

Mirelman, A., Patritti, B. L., Bonato, P., & Deutsch, J. E. (2010). Effects of virtual reality training on gait biomechanics of individuals post-stroke. *Gait & posture*, 31(4), 433-437.

Mohagheghi, A. A., Khan, T., Meadows, T. H., Giannikas, K., Baltzopoulos, V., & Maganaris, C. N. (2007). Differences in gastrocnemius muscle architecture between the paretic and non-paretic legs in children with hemiplegic cerebral palsy. *Clinical biomechanics*, 22(6), 718-724.

Molnar, G.E. (1985). *Cerebral palsy*. In: Molnar GE, editor. Pediatric rehabilitation. Baltimore (MD): Williams & Wilkins; p. 481.

Monfils, M. H., & Teskey, G. C. (2004). Skilled-learning induced potentiation in rat sensorimotor cortex: A transient form of behavioral long-term potentiation. *Neuroscience*, 125, 329–336.

Monfils, M. H., Plautz, E. J., & Kleim, J. A. (2005). In search of the motor engram: Motor map plasticity as a mechanism for encoding motor experience. *Neuroscientist*, 11, 471–483.

Moreau, N. G., Bodkin, A. W., Bjornson, K., Hobbs, A., Soileau, M., & Lahasky, K. (2016). Effectiveness of rehabilitation interventions to improve gait speed in children with cerebral palsy: systematic review and meta-analysis. *Physical therapy*, 96(12), 1938-1954.

Moreau, N. G., Teefey, S. A., & Damiano, D. L. (2009). In vivo muscle architecture and size of the rectus femoris and vastus lateralis in children and adolescents with cerebral palsy. *Developmental Medicine & Child Neurology*, 51(10), 800-806.

Muratori, L. M., Lamberg, E. M., Quinn, L., & Duff, S. V. (2013). Applying principles of motor learning and control to upper extremity rehabilitation. *Journal of Hand Therapy*, 26(2), 94-103.

Murphy KP, Molnar GE, Lankasky K. (1995) Medical and functional status of adults with cerebral palsy. *Dev. Med. Child. Neurol*., 37:1075-1084.

Nagayama, C. (2014). Interventional Spasticity Management for Enhancing Patient–Physician Communications. *IJACSA*, 5(3).

Nakamura, M., Ikezoe, T., Takeno, Y., & Ichihashi, N. (2011). Acute and prolonged effect of static stretching on the passive stiffness of the human gastrocnemius muscle tendon unit in vivo. *Journal of Orthopaedic Research,* 29(11), 1759-1763.

Nam, K. Y., Kim, H. J., Kwon, B. S., Park, J. W., Lee, H. J., & Yoo, A. (2017). Robot-assisted gait training (Lokomat) improves walking function and activity in people with spinal cord injury: a systematic review. *Journal of neuroengineering and rehabilitation*, 14(1), 24.

National Institute of Neurological Disorders and Stroke (NIH). (2010). *Cerebral palsy: hope through research.* Retrieved from

Nelson, K. B. (2002). The epidemiology of cerebral palsy in term infants. *Mental retardation and developmental disabilities research reviews*, 8(3), 146-150.

NHS Choices. (2017). *Cerebral palsy*. Retrieved from: http://www.nhs.uk/conditions/Cerebral-palsy/Pages/Introduction.aspx

Noonan, V. K., Miller, W. C., et al. (2009). "A review of instruments assessing participation in persons with spinal cord injury." *Spinal Cord*, 47(6): 435-446.

Norcross, M. F., Lewek, M. D., Padua, D. A., Shultz, S. J., Weinhold, P. S., & Blackburn, J. T. (2013). Lower extremity energy absorption and biomechanics during landing, part I: sagittal-plane energy absorption analyses. *Journal of athletic training,* 48(6), 748-756.

Nordmark, E., Hägglund, G., & Lagergren, J. (2001). Cerebral palsy in southern Sweden II. Gross motor function and disabilities. *Acta paediatrica*, *90*(11), 1277-1282.

Noreau, L., Desrosiers, J., Robichaud, L., Fougeyrollas, P., Rochette, A., & Viscogliosi, C. (2004). Measuring social participation: reliability of the LIFE-H in older adults with disabilities. *Disability & Rehabilitation*, *26*(6), 346-352.

Novak, I., Mcintyre, S., Morgan, C., Campbell, L., Dark, L., Morton, N., Stumbles, E., Wilson, S.A., & Goldsmith, S. (2013). A systematic review of interventions for children with cerebral palsy: state of the evidence. *Developmental Medicine & Child Neurology*, 55(10), 885-910.

Nowakowski, R.S. (2006). Stable neuron numbers from cradle to grave. *Proceedings of the National Academy of Sciences of the United States of America*, 103(33):12219-12220.

Nudo, R. J. (1997). Remodeling of cortical motor representations after stroke: implications for recovery from brain damage. *Molecular psychiatry*, 2(3), 188.

Nudo, R. J., Milliken, G. W., Jenkins, W. M., & Merzenich, M. M. (1996). Use-dependent alterations of movement representations in primary motor cortex of adult squirrel monkeys. *Journal of Neuroscience*, 16, 785–807.

Nudo, R.J., Plautz, E.J., Milliken, G.W. (1997). Adaptive Plasticity in Primate Motor Cortex as a Consequence of Behavioral Experience and Neuronal Injury. *Seminars in NEUROSCIENCE*, 9, 13–23.

O'Neil, M. E., Fragala-Pinkham, M. A., Westcott, S. L., Martin, K., Chiarello, L. A., Valvano, J., & Rose, R. U. (2006). Physical therapy clinical management recommendations for children with cerebral palsy-spastic diplegia: achieving functional mobility outcomes. *Pediatric physical therapy*, *18*(1), 49-72.

Odman, P. E., & Oberg, B. E. (2006). Effectiveness and expectations of intensive training: a comparison between child and youth rehabilitation and conductive education. *Disability and rehabilitation*, 28(9), 561-570.

Olney, S. J., & Richards, C. (1996). Hemiparetic gait following stroke. Part I: Characteristics. *Gait & posture*, 4(2), 136-148.

Olney, S. J., Griffin, M. P., & McBride, I. D. (1994). Temporal, kinematic, and kinetic variables related to gait speed in subjects with hemiplegia: a regression approach. *Physical therapy*, 74(9), 872-885.

Olney, S. J., MacPhail, H. A., Hedden, D. M., & Boyce, W. F. (1990). Work and power in hemiplegic cerebral palsy gait. *Physical Therapy*, 70(7), 431-438.

Opheim, A., R. Jahnsen, E. Olsson and J. Staghelle (2009). Walking function, pain and fatigue in adults with cerebral palsy: A 7-year follow-up study. *Developmental Medicine & Child Neurology*, 51(5): 381-8.

Orlin, M. N., Palisano, R. J., Chiarello, L. A., KANG, L. J., Polansky, M., Almasri, N., & Maggs, J. (2010). Participation in home, extracurricular, and community activities among children and young people with cerebral palsy.*Developmental Medicine & Child Neurology*, *52*(2), 160-166.

Østensjø, S., Carlberg, E. B., & Vøllestad, N. K. (2004). Motor impairments in young children with cerebral palsy: relationship to gross motor function and everyday activities. *Developmental Medicine & Child Neurology*, 46(9), 580-589.

Page, P. (2012). Current concepts in muscle stretching for exercise and rehabilitation. *International journal of sports physical therapy*, 7(1), 109.

Palisano, R. J., Hanna, S. E., Rosenbaum, P. L., & Tieman, B. (2010). Probability of walking, wheeled mobility, and assisted mobility in children and adolescents with cerebral palsy. *Developmental Medicine & Child Neurology, 52*(1), 66-71. doi: 10.1111/j.1469-8749.2009.03454.x

Palisano, R., Rosenbaum, P., Bartlett, D., & Livingston, M. (2007). GMFCS-E & R Gross Motor Function Classification System: Expanded and Revised. Canchild centre for childhood disability research, Mcmaster University; Institute for Applied Health Sciences McMaster University: Hamilton, ON, Canada.

Palisano, R., Rosenbaum, P., Bartlett, D., & Livingston, M. (2008). Content validity of the expanded and revised gross motor function classification. *Developmental Medicine & Child Neurology, 50,* 744-750. doi: 10.1111/j.1469- 8749.2008.03089.x

Palisano, R.J., Copeland, W.P., Galuppi, B.E. (2007). Performance of physical activities by adolescents with cerebral palsy. *Phys Ther,* 87(1):77-87. Epub 2006 Dec 19.

Park, J. W., & Kim, W. B. (2014). The Effect of Functional Training Using a Sliding Rehabilitation Machine on the Mobility of the Ankle Joint and Balance in Children with CP. *Journal of the Korean Society of Physical Medicine*, 9(3), 293-299.

Parry, R. H., Lincoln, N. B., & Vass, C. D. (1999). Effect of severity of arm impairment on response to additional physiotherapy early after stroke. *Clinical Rehabilitation*, 13(3), 187-198.

Pascual-Leone, A., Nguyet, D., Cohen, L. G., Brasil-Neto, J. P., Cammarota, A., & Hallett, M. (1995). Modulation of muscle responses evoked by transcranial magnetic stimulation during the acquisition of new fine motor skills. *Journal of Neurophysiology*, 74, 1037–1045.

Patrick, E., Ada, L. (2006). The Tardieu Scale differentiates contracture from spasticity whereas the Ashworth Scale is confounded by it. *Clin Rehabil,* 20(2):173-82.

Patritti, B. L., Sicari, M., Deming, L. C., Romaguera, F., Pelliccio, M. M., Kasi, P., Benedetti, M.G., Nimec, D.L & Bonato, P. (2010). The role of augmented feedback in pediatric robotic-assisted gait training: A case series. *Technology and Disability*, 22(4), 215-227.

Paulis, W.D., Horemans, H.L., Brouwer, B.S., et al. (2011). Excellent test−retest and inter-rater reliability for Tardieu Scale measurements with inertial sensors in elbow flexors of stroke patients. *Gait Posture*, 33:185–9.

Perez, M. A., Lungholt, B. K., Nyborg, K., & Nielsen, J. B. (2004). Motor skill training induces changes in the excitability of the leg cortical area in healthy humans. *Experimental Brain Research*, 159, 197–205.

Perier, O. J., Buyse, M., Lechat, J., & Stenuit, A. (1986). Deprivation and morphological changes in the central nervous system. *Acta Oto-laryngolica*, 429(Suppl.), 45–50.

Perry, J., & Burnfield, J. M. (1993). Gait analysis: normal and pathological function. *Developmental Medicine and Child Neurology*, 35, 1122-1122.

Perry, J., & Davids, J. R. (1992). Gait analysis: normal and pathological function. *Journal of Pediatric Orthopaedics*, 12(6), 815.

Picelli, A., Melotti, C., Origano, F., Waldner, A., Gimigliano, R., & Smania, N. (2012). Does robotic gait training improve balance in Parkinson's disease? A randomized controlled trial. *Parkinsonism & related disorders*, 18(8), 990-993.

Picelli, A., Tamburin, S., Passuello, M., Waldner, A., & Smania, N. (2014). Robot-assisted arm training in patients with Parkinson's disease: a pilot study. *Journal of neuroengineering and rehabilitation*, 11(28).

Pierce, S. R., Orlin, M. N., Lauer, R. T., Johnston, T. E., Smith, B. T., & McCarthy, J. J. (2004). Comparison of percutaneous and surface functional electrical stimulation during gait in a child with hemiplegic cerebral palsy. *American journal of physical medicine & rehabilitation*, 83(10), 798-805.

Pitcher, C. A., Elliott, C. M., Williams, S. A., Licari, M. K., Kuenzel, A., Shipman, P. J., Valentine, J.P. & Reid, S. L. (2012). Childhood muscle morphology and strength: alterations over six months of growth. *Muscle & nerve*, 46(3), 360-366.

Puyau, M. R., Adolph, A. L., Vohra, F. A., & Butte, N. F. (2002). Validation and calibration of physical activity monitors in children. *Obesity*, 10(3), 150-157.

Qiu, Q., Adamovich, S., Saleh, S., Lafond, I., Merians, A. S., & Fluet, G. G. (2011, June). A comparison of motor adaptations to robotically facilitated upper extremity task practice demonstrated by children with cerebral palsy and adults with stroke. *In Rehabilitation Robotics (ICORR), 2011 IEEE International Conference on* (pp. 1-5). IEEE.

Qiu, Q., Fluet, G. G., Saleh, S., Ramirez, D., & Adamovich, S. (2010, March). Robot-assisted virtual rehabilitation (NJIT-RAVR) system for children with cerebral palsy. *In Bioengineering Conference, Proceedings of the 2010 IEEE 36th Annual Northeast* (pp. 1-2). IEEE.

Quebec, Q. C. (2007). Measuring participation in children with disabilities using the Assessment of Life Habits. *Developmental Medicine & Child Neurology*, *49*, 666-671.

Rakic, P. (2006). No more cortical neurons for you. *Science*, 313:928-929.

Rauch, A., Cieza, A., Stucki, G., (2008). How to apply the International Classification of Functioning, Disability and Health (ICF) for rehabilitation management in clinical practice. *Eur.J.Phys.Rehabil.Med*. 44, 329-342.

Reddihough and Collins (2003). The epidemiology and causes of cerebral palsy. *Australian Journal of Physiotherapy*, 49, 7-12.

Reeves, N. D., Maganaris, C. N., & Narici, M. V. (2003). Effect of strength training on human patella tendon mechanical properties of older individuals. *The Journal of physiology*, 548(3), 971-981.

Rehabilitation Measures Database (RMD). (2012). *Tardieu Scale/Modified Tardieu Scale*. Retrieved from http://www.rehabmeasures.org/Lists/RehabMeasures/DispForm.aspx?ID=1038.

Reinkensmeyer, D. J., Emken, J. L., & Cramer, S. C. (2004). Robotics, motor learning, and neurologic recovery. *Annu. Rev. Biomed. Eng.*, 6, 497-525.

Reinkensmeyer, D. J., Kahn, L. E., Averbuch, M., McKenna-Cole, A., Schmit, B. D., & Rymer, W. Z. (2000). Understanding and treating arm movement impairment after chronic brain injury: progress with the ARM guide. *Journal of rehabilitation research and development*, 37(6), 653-662.

Resnik, L., & Plow, M. A. (2009). Measuring participation as defined by the international classification of functioning, disability and health: an evaluation of existing measures. *Archives of physical medicine and rehabilitation*, 90(5), 856-866.

Riad, J., Haglund-Akerlind, Y., & Miller, F. (2008). Power generation in children with spastic hemiplegic cerebral palsy. *Gait & posture*, 27(4), 641-647.

Riad, J., Modlesky, C. M., Gutierrez-Farewik, E. M., & Broström, E. (2012). Are muscle volume differences related to concentric muscle work during walking in spastic hemiplegic cerebral palsy?. *Clinical Orthopaedics and Related Research*, 470(5), 1278-1285.

Riener, R., Nef, T., & Colombo, G. (2005). Robot-aided neurorehabilitation of the upper extremities. *Medical and Biological Engineering and Computing*, 43(1), 2-10.

Rimmer, J. H. (2001). Physical fitness levels of persons with cerebral palsy. *Developmental medicine and child neurology*, 43(3), 208-212.

Roberto, C., Fabrizio, P., Carmen, D., Silvestro, M., Chiara, C. M., Paolo, D., & Giuseppe, M. (2007). Design strategies to improve patient motivation during robot-aided rehabilitation. *Journal of Neuro-engineering PMCID*, 300-307.

Rodda, J. M., Graham, H. K., Carson, L., Galea, M. P., & Wolfe, R. (2004). Sagittal gait patterns in spastic diplegia. *Bone & Joint Journal*, 86(2), 251-258.

Rodda, J., & Graham, H. K. (2001). Classification of gait patterns in spastic hemiplegia and spastic diplegia: a basis for a management algorithm. *European journal of neurology*, 8(s5), 98-108.

Rose, J., Gamble, J. G., Burgos, A., Medeiros, J., & Haskell, W. L. (1990). Energy expenditure index of walking for normal children and for children with cerebral palsy. *Developmental Medicine & Child Neurology,* 32(4), 333-340.

Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., & Bax, M. (2007a). A report: the definition and classification of cerebral palsy April 2006. *Developmental Medicine & Child Neurology*, 49, Supplement 109, 8-14. doi: 10.1111/j.14698749.2007.tb12610.x

Rosenbaum, P., Paneth, N., Leviton, A., Goldstein, M., & Bax, P. (2007). The Definition and Classification of Cerebral Palsy. *Developmental Medicine & Child Neurology, 49*, 1-44.

Rosenberger, A., Beijer, Å., Johannes, B., Schoenau, E., Mester, J., Rittweger, J., & Zange, J. (2017). Changes in muscle cross-sectional area, muscle force, and jump performance during 6 weeks of progressive whole-body vibration combined with progressive, high intensity resistance training. *Journal of musculoskeletal & neuronal interactions*, 17(2), 38.

Ross, S. A., & Engsberg, J. R. (2002). Relation between spasticity and strength in individuals with spastic diplegic cerebral palsy. *Developmental medicine and child neurology*, 44(3), 148-157.

Ross, S. A., & Engsberg, J. R. (2007). Relationships between spasticity, strength, gait, and the GMFM-66 in persons with spastic diplegia cerebral palsy. *Archives of physical medicine and rehabilitation*, 88(9), 1114-1120.

Ross, S. A., Engsberg, J. R., & Collins, D. R. (2006). Ankle Strengthening To Improve Gait And Function In Cerebral Palsy—a Pilot Study. *Pediatric Physical Therapy*, 18(1), 80-81.

Rossi, S., Colazza, A., Petrarca, M., Castelli, E., Cappa, P., & Krebs, H. I. (2013). Feasibility study of a wearable exoskeleton for children: is the gait altered by adding masses on lower limbs. *PloS one*, 8(9).

Roy, A., Forrester, L.W., & Macko, R. F. (2011). Short-term ankle motor performance with ankle robotics training in chronic hemiparetic stroke. *Journal of rehabilitation research and development*, 48(4), 417.

Roy, A., Forrester, L.W., Macko, R.F., & Krebs, H.I. (2013). Changes in passive ankle stiffness and its effects on gait function in people with chronic stroke. *Journal of rehabilitation research and development*, 50(4), 555.

Roy, A., Krebs, H. I., Williams, D. J., Bever, C. T., Forrester, L. W., Macko, R. M., & Hogan, N. (2009). Robot-aided neurorehabilitation: a novel robot for ankle rehabilitation. *Robotics, IEEE Transactions on*, 25(3), 569-582.

Sakzewski, L., Boyd, R., et al. (2007). "Clinimetric properties of participation measures for 5- to 13-year-old children with cerebral palsy: a systematic review." *Dev Med Child Neurol*, 49(3): 232-240.

Sakzewski, L., Ziviani, J., & Boyd, R. (2009). Systematic review and meta-analysis of therapeutic management of upper-limb dysfunction in children with congenital hemiplegia. *Pediatrics,* 123(6), e1111-e1122.

Samosawala, N. R., Vaishali, K., & Kalyana, B. C. (2016). Measurement of muscle strength with handheld dynamometer in Intensive Care Unit. *Indian journal of critical care medicine: peer-reviewed, official publication of Indian Society of Critical Care Medicine*, 20(1), 21.

Sawaki L, Butler AJ, Xiaoyan L, Wassenaar PA, Mohammad YM, Blanton, S., et al. (2008). Constraint-induced movement therapy results in increased motor map area in subjects 3 to 9 months after stroke. *Neurorehabil Neural Repair*, 22: 505–13.

Schenker, R., Coster, W. J., & Parush, S. (2005). Neuroimpairments, activity performance, and participation in children with cerebral palsy mainstreamed in elementary schools. *Developmental medicine and child neurology,* 47(12), 808-814.

Schenker, R., Coster, W., & Parush, S. (2005). Participation and activity performance of students with cerebral palsy within the school environment. *Disability and rehabilitation*, 27(10), 539-552.

Seeger, B. R., Caudrey, D. J., & O'Mara, N. A. (1984). Hand function in cerebral palsy: the effect of hip-flexion angle. *Developmental Medicine & Child Neurology*, 26(5), 601-606.

Selles, R. W., Li, X., Lin, F., Chung, S. G., Roth, E. J., & Zhang, L. Q. (2005). Feedback-controlled and programmed stretching of the ankle plantarflexors and dorsiflexors in stroke: effects of a 4-week intervention program. *Archives of physical medicine and rehabilitation*, 86(12), 2330-2336.

Shankman, G. A., & Manske, R. C. (2014). *Fundamental orthopedic management for the physical therapist assistant* (pp. 229). Elsevier Health Sciences.

Shea CH, Kohl RM (1991). Composition of practice: influence on the retention of motor skills. *Res Q Exerc Sport*, 62: 187–195.

Shea, J. B., & Morgan, R. L. (1979). Contextual interference effects on the acquisition, retention, and transfer of a motor skill. *Journal of Experimental Psychology: Human Learning and Memory*, *5*(2), 179.

Shepherd, R. B. (1980). *Physiotherapy in paediatrics* (pp 110-4). Heinemann Medical Books.

Shepherd, R.B. (1995). *Physiotherapy in paediatrics*. 3rd edition, Oxford: Butterworth-Heinemann.

Shonkoff, J.P., Hauser-Cram, P. (1987). Early intervention for disabled infants and their families: a quantitative analysis. *Pediatrics,* 80:650.

Shumway-Cook, A., & Woollacott, M. H. (1995). *Motor control: theory and practical applications*. Lippincott Williams & Wilkins.

Shumway-Cook, A., Hutchinson, S., Kartin, D., Price, R., & Woollacott, M. (2003). Effect of balance training on recovery of stability in children with cerebral palsy. *Developmental Medicine and Child Neurology*, 45(9), 591-602.

Sidaway, B., Bates, J., Occhiogrosso, B., Schlagenhaufer, J., & Wilkes, D. (2012). Interaction of feedback frequency and task difficulty in children's motor skill learning. *Physical therapy*, 92(7), 948-957.

Simpkins, S. D., Ripke, M., Huston, A. C., & Eccles, J. S. (2005). Predicting participation and outcomes in out-of-school activities: Similarities and differences across social ecologies. *New Directions for Student Leadership*, 2005(105), 51-69.

Singh, P., Joshua, A.M., Ganeshan,S., and Suresh, S. (2011). Intra-rater reliability of the modified Tardieu scale to quantify spasticity in elbow flexors and ankle plantar flexors in adult stroke subjects. *Ann Indian Acad Neurol,* 14(1): 23–26.

Sledziewski, L., Schaaf, R. C., & Mount, J. (2012). Use of robotics in spinal cord injury: A case report. *American Journal of Occupational Therapy*, 66(1), 51-58.

Smania, N., Bonetti, P., Gandolfi, M., Cosentino, A., Waldner, A., Hesse, S., et al. (2011). Improved gait after repetitive locomotor training in children with cerebral palsy. *American Journal of Physical Medicine & Rehabilitation,90*(2), 137-149.

Smith, L. B., & Thelen, E. (1993). *A dynamic systems approach to development: Applications.* Cambridge, MA: The MIT Press / Bradford Books.

Smits, D.W., van Groenestijn, A.C., Ketelaar, M., Scholtes, V.A., Becher, J.G., Gorter, J.W. (2010). Selective motor control of the lower extremities in children with cerebral palsy: inter-rater reliability of two tests. *Dev Neurorehabil*, 13(4):258-65.

Sopher, R. S., Amis, A. A., Davies, D. C., & Jeffers, J. R. (2017). The influence of muscle pennation angle and cross-sectional area on contact forces in the ankle joint. The Journal of Strain Analysis for Engineering Design, 52(1), 12-23.

Sorsdahl, A. B., Moe-Nilssen, R., & Strand, L. I. (2008). Test–retest reliability of spatial and temporal gait parameters in children with cerebral palsy as measured by an electronic walkway. *Gait & posture*, 27(1), 43-50.

Spink, M. J., Fotoohabadi, M. R., & Menz, H. B. (2010). Foot and ankle strength assessment using hand-held dynamometry: reliability and age-related differences. *Gerontology*, 56(6), 525-532.

Spink, M. J., Fotoohabadi, M. R., Wee, E., Hill, K. D., Lord, S. R., & Menz, H. B. (2011). Foot and ankle strength, range of motion, posture, and deformity are associated with balance and functional ability in older adults. *Archives of physical medicine and rehabilitation*, 92(1), 68-75.

Staudt, M. (2010). Brain plasticity following early life brain injury: insights from neuroimaging. *Semin Perinatol*, 34(1):87-92. doi: 10.1053/j.semperi.2009.10.009.

Stein, J., Krebs, H. I., Frontera, W. R., Fasoli, S. E., Hughes, R., & Hogan, N. (2004). Comparison of two techniques of robot-aided upper limb exercise training after stroke. *American journal of physical medicine & rehabilitation*, 83(9), 720-728.

Steinau, H. U., Tofaute, A., Huellmann, K., Goertz, O., Lehnhardt, M., et al. (2011). Tendon transfers for drop foot correction: long-term results including quality of life assessment, and dynamometric and pedobarographic measurements. *Archives of orthopaedic and trauma surgery*, 131(7), 903-910.

Stevenson, C. J., Pharoah, P. O. D., & Stevenson, R. (1997). Cerebral palsy-the transition from youth to adulthood. *Developmental Medicine & Child Neurology*, 39(5), 336-342.

Strasser, E. M., Draskovits, T., Praschak, M., Quittan, M., & Graf, A. (2013). Association between ultrasound measurements of muscle thickness, pennation angle, echogenicity and skeletal muscle strength in the elderly. *Age*, 35(6), 2377-2388.

Sung, D. H., & Bang, H. J. (2000). Motor branch block of the rectus femoris: its effectiveness in stiff-legged gait in spastic paresis. *Archives of physical medicine and rehabilitation*, 81(7), 910-915.

Sutherland, D. H., Davids, J. R., (1993). Common gait abnormalities of the knee in cerebral palsy. *Clin.Orthop.Relat.Res.* 139-147.

Swinnen, E., Beckwée, D., Meeusen, R., Baeyens, J. P., & Kerckhofs, E. (2014). Does robot-assisted gait rehabilitation improve balance in stroke patients? A systematic review. *Topics in stroke rehabilitation*, 21(2), 87-100.

Takahashi, C. D., Der-Yeghiaian, L., Le, V., Motiwala, R. R., & Cramer, S. C. (2008). Robot-based hand motor therapy after stroke. Brain, 131(2), 425-437.

Takata, N. (1974). *Play as prescription*. In M. Reilly (Ed.), Play as exploratory learning. Beverly Hills, CA: Sage Publications.

Tardieu, G., Shentoub, S., & Delarue, R. (1954). * A LA RECHERCHE DUNE TECHNIQUE DE MESURE DE LA SPASTICITE. *Revue neurologique*, *91*(2), 143-144.

Taub, E., Miller, N. E., Novack, T. A., Fleming, W. C., Nepomuceno, C. S., Connell, J. S., & Crago, J. E. (1993). Technique to improve chronic motor deficit after stroke. *Archives of physical medicine and rehabilitation*, 74(4), 347-354.

Taub, E., Uswatte, G., & Pidikiti, R. (1999). Constraint-Induced Movement Therapy: a new family of techniques with broad application to physical rehabilitation--a clinical review. *Journal of rehabilitation research and development*, 36(3), 237

Taylor, N. F., Dodd, K. J., & Damiano, D. L. (2005). Progressive resistance exercise in physical therapy: a summary of systematic reviews. *Physical therapy*, 85(11), 1208-1223.

Teixeira-Salmela, L. F., Nadeau, S., Milot, M. H., Gravel, D., & Requião, L. F. (2008). Effects of cadence on energy generation and absorption at lower extremity joints during gait. *Clinical biomechanics*, 23(6), 769-778.

Temes, W. C., Temes Clifton, A., Hilton, V., Girard, L., Strait, N., & Karduna, A. (2014). Reliability and validity of thickness measurements of the supraspinatus muscle of the shoulder: an ultrasonography study. *J Sport Rehabil*, 2013-0023.

The Conference Board (TCB). (2014). *Growing Labor Shortages on the Horizon in Mature Economies.* Retrieved from https://www.conference-board.org/press/pressdetail.cfm?pressid=5266

THE UNITED CEREBRAL PALSY RESEARCH FOUNDATION AND EDUCATIONAL FOUNDATION., 1999. *Exercise principles and guidelines for persons with cerebral palsy and neuromuscular disorders*. Retrieved from: http://www.ucpaindy.org/wp-content/uploads/2010/03/Exercise-Principles-and-Guidelines-for-Persons-with-Cerebral-Palsy-and-Neuromuscular-Disorders.pdf

Thelen, E. (1989). The (re)discovery of motor development: Learning new things from an old field. *Developmental Psychology*, 25(6), 946-949.

Thelen, E., & Smith, L. B. (1998). Dynamic systems theories. Handbook of child psychology.

Thelen, E., Kelso, J. S., & Fogel, A. (1987). Self-organizing systems and infant motor development. *Developmental Review*, 7(1), 39-65.

Thorborg, K., Petersen, J., Magnusson, S. P., & Hölmich, P. (2010). Clinical assessment of hip strength using a hand-held dynamometer is reliable. *Scandinavian journal of medicine & science in sports*, 20(3), 493-501.

Toner, L. V., Cook, K., & Elder, G. C. (1998). Improved ankle function in children with cerebral palsy after computer-assisted motor learning. *Developmental Medicine & Child Neurology*, 40(12), 829-835.

Trost, S. G., Pate, R. R., Freedson, P. S., Sallis, J. F., & Taylor, W. C. (2000). Using objective physical activity measures with youth: how many days of monitoring are needed?. *Medicine & Science in Sports & Exercise*, 32(2), 426.

Tugui, R. D., & Antonescu, D. (2013). Cerebral palsy gait, clinical importance. *Maedica*, 8(4), 388.

Tuzson, A. E., Granata, K. P., & Abel, M. F. (2003). Spastic velocity threshold constrains functional performance in cerebral palsy. *Archives of physical medicine and rehabilitation*, 84(9), 1363-1368.

Tuzun, E. H., Eker, L., & Daskapan, A. (2004). An assessment of the impact of cerebral palsy on children's quality of life. *Fizyoterapi Rehabilitasyon*, 15(1), 3.

Umberger, B. R., & Martin, P. E. (2007). Mechanical power and efficiency of level walking with different stride rates. *Journal of Experimental Biology*, 210(18), 3255-3265.

UNH. (2014). Annual Disability Statistics Compendium. Retrieved from http://disabilitycompendium.org/compendium-statistics/employment

Vaes, P. H., Duquet, W., Casteleyn, P. P., Handelberg, F., & Opdecam, P. (1998). Static and dynamic roentgenographic analysis of ankle stability in braced and nonbraced stable and functionally unstable ankles. *The American journal of sports medicine*, 26(5), 692-702.

Van der Krogt, M. M. (2009). *Gait deviations in children with cerebral palsy: a modeling approach*. Research Institute MOVE, VU University Medical Center Amsterdam, the Netherlands.

van Groenestijn MSc, A. C., & van Schie MSc, P. E. M. Clinical assessment of selective motor control in children aged 5-7 years with cerebral palsy.

Van Peppen, R. P., Kwakkel, G., Wood-Dauphinee, S., Hendriks, H. J., Van der Wees, P. J., & Dekker, J. (2004). The impact of physical therapy on functional outcomes after stroke: what's the evidence?. *Clinical rehabilitation*, *18*(8), 833-862.

Van Zelst, B. R., Miller, M. D., Russo, R. N., Murchland, S., & Crotty, M. (2006). Activities of daily living in children with hemiplegic cerebral palsy: a cross-sectional evaluation using the assessment of motor and process skills. *Developmental medicine and child neurology*, 48(9), 723-727.

Varghese, A., & Bianchi, S. (2014). Ultrasound of tibialis anterior muscle and tendon: anatomy, technique of examination, normal and pathologic appearance. *Journal of ultrasound*, 17(2), 113-123.

Vargus-Adams, J. (2005). Health-related quality of life in childhood cerebral palsy. *Archives of physical medicine and rehabilitation*, 86(5), 940-945.

Verschuren, O., Ketelaar, M., Takken, T., Van Brussel, M., Helders, P. J., & Gorter, J. W. (2008). Reliability of hand-held dynamometry and functional strength tests for the lower extremity in children with cerebral palsy. *Disability and rehabilitation,* 30(18), 1358-1366.

Volpe, B. T., Krebs, H. I., Hogan, N., Edelstein, L., Diels, C., & Aisen, M. (2000). A novel approach to stroke rehabilitation Robot-aided sensorimotor stimulation. *Neurology*, 54(10), 1938-1944.

Wallen, M., O'Flaherty, S.J., Waugh, M.C. (2007). Functional outcomes of intramuscular botulinum toxin type A and occupational therapy in the upper limbs of children with cerebral palsy: a randomized controlled trial. *Arch Phys Med Rehabil*, 88(1):1-10.

Waninge, A., Rook, R.A., Dijkhuizen, A., Gielen, E., van der Schans, C.P. (2011). Feasibility, test-retest reliability, and interrater reliability of the Modified Ashworth Scale and Modified Tardieu Scale in persons with profound intellectual and multiple disabilities. *Res Dev Disabil*, 32(2):613-20.

Ward, D. S., Evenson, K. R., Vaughn, A., Rodgers, A. B., & Troiano, R. P. (2005). Accelerometer use in physical activity: best practices and research recommendations. *Medicine and science in sports and exercise,* 37(11 Suppl), S582-8.

Warken, B., Graser, J. V., Ulrich, T., Borggraefe, I., Heinen, F., Meyer-Heim, A., et al. S. (2015). Practical Recommendations for Robot-Assisted Treadmill Therapy (Lokomat) in Children with Cerebral Palsy: Indications, Goal Setting, and Clinical Implementation within the WHO-ICF Framework. *Neuropediatrics,* 46(4):248-60. doi: 10.1055/s-0035-1550150.

Waters, R.L., & Mulroy, S. (1999) The energy expenditure of normal and pathologic gait. *Gait Posture*, 9: 207–231.

Wei, S., Su-Juan, W., Yuan-Gui, L., et al. (2006). Reliability and validity of the GMFM-66 in 0-3 year-old children with Cerebral Palsy. *Am J Phys Med Rehabil*, 85:141–7.

Weinberger, N. M. (2004). Specific long-term memory traces in primary auditory cortex. *Nature Reviews Neuroscience*, 5, 279–290.

Westbom, L., Hagglund, G., Nordmark, E. (2007). Cerebral palsy in a total population of 4–11 year olds in southern Sweden. Prevalence and distribution according to different CP classification systems. *BMC Pediatr*, 7: 41.

Whiteneck, G. (2006, February). *Conceptual models of disability: past, present, and future.* In Workshop on disability in America: A new look (pp. 50-66). Washington DC: The National Academies Press.

Wiart, L., Darrah, J., & Kembhavi, G. (2008). Stretching with children with cerebral palsy: what do we know and where are we going?. *Pediatric physical therapy*, 20(2), 173-178.

Wichers, M., Hilberink, S., Roebroeck, M. E., van Nieuwenhuizen, O., & Stam, H. J. (2009). Motor impairments and activity limitations in children with spastic cerebral palsy: a Dutch population-based study. *Journal of rehabilitation medicine*, 41(5), 367-374.

Wier, L. M., Hatcher, M. S., & Lo, A. C. (2011). Effect of robot-assisted versus conventional body-weight-supported treadmill training on quality of life for people with multiple sclerosis. *Journal of rehabilitation research and development*, 48(4), 483.

Wiley, M. E., & Damiano, D. L. (1998). Lower-Extremity strength profiles in spastic cerebral palsy. *Developmental Medicine & Child Neurology*, 40(2), 100-107.

Willerslev-Olsen, M., Lorentzen, J., Sinkjær, T., & Nielsen, J. B. (2013). Passive muscle properties are altered in children with cerebral palsy before the age of 3 years and are difficult to distinguish clinically from spasticity. *Developmental medicine & Child neurology*, 55(7), 617-623.

Winter DA (1991) *The Biomechanics and Motor Control of Human Gait: Normal, Elderly and Pathological*. Waterloo: Waterloo Biomechanics.

Winters, T. F., Gage, J. R., & Hicks, R. (1987). Gait patterns in spastic hemiplegia in children and young adults. *J Bone Joint Surg Am*, 69(3), 437-441.

Wirz, M., Zemon, D. H., Rupp, R., Scheel, A., Colombo, G., Dietz, V., & Hornby, T. G. (2005). Effectiveness of automated locomotor training in patients with chronic incomplete spinal cord injury: a multicenter trial. *Archives of physical medicine and rehabilitation*, 86(4), 672-680.

Wood, K. C., Lathan, C. E., & Kaufman, K. R. (2013). Feasibility of gestural feedback treatment for upper extremity movement in children with cerebral palsy. *Neural Systems and Rehabilitation Engineering, IEEE Transactions on*, 21(2), 300-305.

Woollacott, M. H., & Shumway-Cook, A. (2005). Postural dysfunction during standing and walking in children with cerebral palsy: what are the underlying problems and what new therapies might improve balance?. *Neural plasticity*, 12(2-3), 211-219.

World Health Organization (WHO). (2001). *International Classification of Functioning, Disability and Health: ICF*. Geneva, Switzerland: World Health Organization.

World Health Organization (WHO). (2002). *Towards a common language for functioning, disability and health: ICF*.

World Health Organization (WHO). (2015). *International Classification of Functioning, Disability and Health (ICF).* Retrieved from http://www.who.int/classifications/icf/icf_more/en/

Wren, T. A., Rethlefsen, S., & Kay, R. M. (2005). Prevalence of specific gait abnormalities in children with cerebral palsy: influence of cerebral palsy subtype, age, and previous surgery. *Journal of Pediatric Orthopaedics*, 25(1), 79-83.

Wright, D. L., Black, C. B., Immink, M. A., Brueckner, S., & Magnuson, C. (2004). Long-term motor programming improvements occur via concatenation of movement sequences during random but not during blocked practice. *Journal of Motor Behavior*, *36*(1), 39-50.

Wu, Y. N., Hwang, M., Ren, Y., Gaebler-Spira, D., & Zhang, L. Q. (2011). Combined passive stretching and active movement rehabilitation of lower-limb impairments in children with cerebral palsy using a portable robot. *Neurorehabilitation and neural repair*, 25(4), 378-385.

Wuebbenhorst, K., & Zschorlich, V. (2011). Effects of muscular activation patterns on the ankle joint stabilization: an investigation under different degrees of freedom. *Journal of Electromyography and Kinesiology*, 21(2), 340-347.

Yam, W.K. and Leung, M.S. (2006). Interrater reliability of Modified Ashworth Scale and Modified Tardieu Scale in children with spastic cerebral palsy. *J Child Neurol*, 21(12): 1031-1035.

Zarrugh, M. Y., & Radcliffe, C. W. (1978). Predicting metabolic cost of level walking. *European Journal of Applied Physiology and Occupational Physiology*, 38(3), 215-223.

Zhang, L. Q., Chung, S. G., Bai, Z., Xu, D., van Rey, E. M., Rogers, M. W., Johnson, M.E. & Roth, E. J. (2002). Intelligent stretching of ankle joints with contracture/spasticity. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 10(3), 149-157.

Zhang, M., Davies, T. C., & Xie, S. (2013). Effectiveness of robot-assisted therapy on ankle rehabilitation–a systematic review. *J Neuroeng Rehabil*, 10(1), 30.

Zwicker, J. G., & Harris, S. R. (2009). A reflection on motor learning theory in pediatric occupational therapy practice. *Canadian Journal of Occupational Therapy*, 76(1), 29-37.

CURRICULUM VITAE

Madawi H. Alotaibi

Education

Indiana University Purdue University- Indianapolis, IN

Doctor of Philosophy (2018)

Major: Health and Rehabilitation Sciences

Minor: Health Policy and Management

University of Indianapolis- Indianapolis, IN

Master of Health Sciences (2011)

King Saud University- Riyadh, KSA

Bachelor of Science in Physical Therapy (2006)

Awards

Golden Key International Honor Society

Training Experience and Clinical Internship

Prince Faisal Sport Medicine Hospital- Inpatient Rehabilitation (January-April 2006)

Riyadh Armed Forces Hospital- Medical Surgical, ICU, Orthopedic rehabilitation (May-August 2006)

Security Forces Hospital- Pediatric Rehabilitation, Outpatient Physical Therapy (September-December 2006)

Professional Experience

King Saud Medical Complex- Children Hospital- Physical Therapy Department

(May 2007- December 2008)

Conferences Attended

Poster presentation at the Academy of Pediatric Physical Therapy Annual Conference (APPTAC) (November 2017)

Publications

Alotaibi, M., Long, T., Kennedy, E., & Bavishi, S. (2014). The efficacy of GMFM-88 and GMFM-66 to detect changes in gross motor function in children with cerebral palsy (CP): a literature review. Disability and Rehabilitation, 36(8), 617-627.