The Design and Evaluation of an Interactive Musical Staircase on Physical Rehabilitation Therapies for Children

by

Ajmal Khan

A thesis submitted in conformity with the requirements for the degree of Master of Health Science
Institute of Biomaterials and Biomedical Engineering
University of Toronto

© Copyright by Ajmal Khan 2012
The Design and Evaluation of an Interactive Musical Staircase on Physical Rehabilitation Therapies for Children

Ajmal Khan
Master of Health Science
Institute of Biomaterials and Biomedical Engineering
University of Toronto
2012

Abstract

Stair-climbing is an important skill for promoting independence and activities of daily life and is a key component of rehabilitation therapies for physically disabled children. This thesis describes the design and evaluation of an interactive musical stairs system for children engaged in stair-climbing physical therapies. The achievement of a targeted therapeutic goal, namely, use of reciprocal steps, was significantly increased by 6% [SD=7%] (p=0.007) with the presence of audio feedback. Levels of participant enjoyment and motivation increased as well. This led to the development of an automated system, using inertial sensors to detect initial contact (IC) events each time a child makes a step, to trigger audio feedback. A semi-generic algorithm was designed that was able to detect 96% [SD=3%] of IC events during stair-climbing therapy sessions. This thesis lays the groundwork for future longitudinal research investigating the efficacy of audio feedback in stair-climbing and other rehabilitation therapies as well.
Dedication

To my lovely daughter Zainab, your beautiful smiles and loving looks have been my inspiration. And your screams and tears have been a wonderful distraction!

To my supportive wife Amna, thank you for your love, patience and understanding. I would not be at this point without you.

To my parents, thank you for your endless support of my ambitions. Your continued love and encouragements have brought me to this point.
Acknowledgments

First and foremost, I would like to thank Allah the Almighty for giving me this opportunity and the capability to proceed successfully, for it would not have been possible without his grace.

I would like to thank my thesis supervisor, Dr. Elaine Biddiss, whose unwavering faith in my abilities has been a constant source of inspiration. I would also like to thank my committee members, Dr. Tom Chau and Dr. Virginia Wright, for their unique insights and perspectives that have helped shaped this thesis, and Dr. Jan Andrysek for his helpful feedback and advice.

I am indebted to the great lengths the Integrated Education Therapy team at Holland Bloorview Kids Rehabilitation Hospital have gone to in assisting in my research studies. I am grateful to Claire Mackenzie and Adriana Kubon for helping recruit participants and for answering my endless questions, and Zuzana Firment and Lori Goldlust for their amazing support of the data collection process. I would also like to thank Alan Wu for his skillful camera work during data collection and Chandrashekhar Yaduvanshi for his careful analysis of the video recordings.

To my steering committee, Andrea Primmer, Jennifer Dehoney, Viola Cheng, Erin Stanley, and Claire MacKenzie, thank you for your valuable input in guiding the design process.

I would like to extend a special thanks to all the kids that participated in this study. Your joy and enthusiasm have been a great inspiration for me.

I am also thankful for the advice, discussions, feedback and needed distractions of the members past and present of the LiveIT and PRISM labs.

To my family, I could not have done this without your endless support. Thank you for believing in me and providing me the motivation to succeed.

This research was supported in part by the Holland Bloorview Kids Rehabilitation Hospital Foundation. I am very grateful for their financial support.
# Table of Contents

Dedication ................................................................................................................................. ii  
Acknowledgments ..................................................................................................................... iv  
Table of Contents .................................................................................................................... v  
List of Tables ............................................................................................................................ viii  
List of Figures ............................................................................................................................ ix  
Chapter 1 .................................................................................................................................... 1  
  1 Introduction ............................................................................................................................. 1  
    1.1 Motivation ............................................................................................................................. 1  
    1.2 Research Objectives and Hypotheses ................................................................................. 2  
    1.3 Thesis Layout ....................................................................................................................... 3  
Chapter 2 .................................................................................................................................... 5  
  2 The Impact of Musical Stairs on Stair-Climbing Physical Therapy for Children.................... 5  
    2.1 Abstract ............................................................................................................................... 5  
    2.2 Introduction .......................................................................................................................... 5  
    2.3 Methods .............................................................................................................................. 7  
      2.3.1 Study Design ................................................................................................................... 7  
      2.3.2 Participants .................................................................................................................... 7  
      2.3.3 Data Collection Instruments ......................................................................................... 8  
      2.3.4 Study Protocol ............................................................................................................... 10  
      2.3.5 Data Analysis ............................................................................................................... 11  
    2.4 Results ............................................................................................................................... 11  
      2.4.1 Therapeutic Goal: Reciprocal Steps ............................................................................. 11  
      2.4.2 P-CERT and Smileyometer Scales ................................................................................ 12
2.4.3 Questionnaires............................................................... 13
2.4.4 Blinded Video Analysis ..................................................... 14
2.5 Discussion ............................................................................. 16
  2.5.1 Key Findings................................................................. 16
  2.5.2 Child, PTA, and Technology Interaction ......................... 16
  2.5.3 Study Limitations............................................................ 17
  2.5.4 Future Work ................................................................. 18
2.6 Conclusion ............................................................................. 20
Chapter 3 ..................................................................................... 22
  3 Real Time Detection of Pathological Gait Events during Stair Climbing in Children using Portable Sensors ......................................................... 22
    3.1 Abstract ......................................................................... 22
    3.2 Introduction ..................................................................... 22
    3.3 Methods .......................................................................... 25
      3.3.1 Instrumentation .......................................................... 25
      3.3.2 Participants ............................................................... 26
      3.3.3 Study Protocol ........................................................... 26
      3.3.4 Data Analysis ............................................................. 27
    3.4 Results .............................................................................. 31
      3.4.1 Phase 1 ................................................................. 31
      3.4.2 Phase 2 ................................................................. 35
    3.5 Discussion ......................................................................... 38
      3.5.1 Key Findings ............................................................ 38
      3.5.2 Strengths and Limitations ........................................... 38
      3.5.3 Future Work ............................................................. 41
    3.6 Conclusion ......................................................................... 41
Chapter 4........................................................................................................... 42

4 Conclusion......................................................................................................... 42

4.1 Summary of Contributions............................................................................ 42

4.2 Directions for Future Research ..................................................................... 42

4.3 Closing Remarks............................................................................................. 43

References........................................................................................................... 45

Appendices........................................................................................................... 49
List of Tables

Table 1 - Summary of participant diagnoses (n=17). ................................................................. 8

Table 2 - Details of the participant questionnaire. Responses were either Yes or No. ............... 9

Table 3 - Details of the PTA questionnaire. Responses ranged from Strongly Agree to Strongly Disagree. .......................................................................................................................... 10

Table 4 - The average breakdown of the session time with respect to the time the participants face is visible on camera and the percentage of visible facial time the participant is smiling. (n=16).................................................................................................................................................. 14

Table 5 - Summary of participant diagnoses for Phase 1 and 2.................................................... 26

Table 6 - Summary of results for the IC detection algorithm. A (*) indicates a significant (p < 0.025) change when comparing generalized to individualized algorithms. (n=18) .............. 31

Table 7 - Algorithm parameters used for each participant. (n=18)................................................. 34

Table 8 - Summary of results for the IC detection algorithm on Phase 2 data. A (*) indicates a significant (p < 0.025) change when comparing generalized to semi-generalized algorithms. (n=8) ........................................................................................................................................... 35
List of Figures

Figure 1 - The "Piano Stairs" installed next to an escalator in a subway station in Stockholm. .... 2

Figure 2 - A comparison of the reciprocal steps taken by each participant both with and without
audio feedback. (/100) (n=16) .......................................................................................................... 12

Figure 3 - Summary of the P-CERT scores both with and without audio feedback. (/10) (n=11) 13

Figure 4 - Summary of the Smileyometer scores both with and without audio feedback. (/5)
(n=12) ........................................................................................................................................ 13

Figure 5 - The median ratings of the blinded observer. A significant difference (p < 0.05)
between no audio feedback and the presentation of audio feedback is indicated by (*). (n=16) . 15

Figure 6 - The orientation of the sensor coordinate system......................................................... 25

Figure 7 - The orientation of the anterior-posterior axis in the body and sensor frames .......... 28

Figure 8 - IC event detection accuracy across four algorithm scenarios, both generalized and
individualized, considering both progressive (P) and non-progressive (NP) steps. (n=18) ....... 32

Figure 9 - IC event absolute timing error across four algorithm scenarios, both generalized and
individualized, considering both progressive (P) and non-progressive (NP) steps. Of note, a
mixture of lags (44%) and leads (56%) in timing error were observed. (n=18) ....................... 32

Figure 10 - Percentage of false positives across four algorithm scenarios, both generalized and
individualized, considering both progressive (P) and non-progressive (NP) steps. (n=18) ....... 33

Figure 11 - IC event detection accuracy across four parameter sets in Phase 2, both generalized
and semi-generalized, considering both progressive (P) and non-progressive (NP) steps. (n=8) 36

Figure 12 – IC event absolute timing error across four algorithm scenarios in Phase 2, both
generalized and semi-generalized, considering both progressive (P) and non-progressive (NP)
steps. Of note, a mixture of lags (46%) and leads (54%) in timing error were observed. (n=8) .. 36
Figure 13 - Percentage of false positives across four algorithm scenarios in Phase 2, both generalized and semi-generalized, considering both progressive (P) and non-progressive (NP) steps. (n=8)
List of Abbreviations

FP: False Positive

GMFCS: Gross Motor Function Classification System

IC: Initial Contact

IET: Integrated Education and Therapy

Physical Therapist Assistant: PTA

VR: Virtual Reality
Chapter 1

1 Introduction

1.1 Motivation

Research has shown that children respond positively when interactive environments are used in physical therapy\(^1\). When a child interacts with the environment of their therapy, it creates a sense of play and enjoyment\(^2\) and may also enhance the child’s engagement in the session. Previous studies have noted a measurable improvement in outcomes when a person is highly motivated in their physical therapy\(^3\). There are many people that require physical therapy, such as school-aged children with cerebral palsy (2-3 out of every 1000)\(^4\) and the thousands of Canadians who suffer from brain injuries, many of whom are young adults\(^5\). Physical therapy sessions for patients with cerebral palsy, brain injuries, and lower limb amputations typically include gait therapy as a key focus\(^6\). Gait training aims to improve the patient’s gait while performing various activities, such as walking and stair-climbing. Conventional stairs used in these therapy sessions do not provide therapists with any quantitative feedback relating to the patient’s progress nor do they provide motivational incentives to the patient. As a result, the physical and cognitive loads placed on therapists to physically and emotionally support patients through therapy sessions can be quite demanding.

Exploring this concept of what motivates us, Volkswagen recently held a competition called “Fun Theory”, that investigated the concept of making things fun in order to motivate people to change their behaviour for the better\(^7\). The contest generated several unique ideas on how fun can be applied to change people’s behaviour in a wide variety of ways. One relevant entry in the contest is known as the “Piano Stairs”\(^8\). This entry explored the idea that if climbing stairs was fun, would that motivate people to take the stairs versus an escalator? The group tested out this theory by modifying a set of stairs to look like piano keys and more importantly, to actually play different piano key notes when each step was climbed. These “Piano Stairs” were located in a busy subway station in Stockholm, Sweden, next to an escalator, as shown in Figure 1. As hypothesized, 66% more people elected to take the stairs instead of the adjoining escalator when the experience was designed to be fun and interactive.
At Bloorview School Authority, the Integrated Education and Therapy (IET) program combines various therapy sessions, including physical therapy, with the child’s classroom program for children with a range of physical difficulties. The IET program is available for children aged 4-6. One of the skills that is developed during the physical therapy sessions is stair climbing. A challenge that therapists face with this young population is providing motivation to climb the stairs. We can make stair climbing therapy sessions more motivating by providing an interactive, fun, and engaging experience. So what would happen if we applied the “Piano Stairs” idea to the stair climbing therapy sessions in the IET program? That is, what impact would interactive musical stairs have on physical therapy sessions for children? Exploring this question was the overarching goal of this thesis.

1.2 Research Objectives and Hypotheses

The objectives of this thesis were to design and evaluate a musical feedback system to be used in stair-climbing therapies with young children. Specific objectives associated with the evaluation and design of this system are outlined as follows:

Objective 1: Evaluation of Musical Feedback

(1) To determine the impact on enjoyment, exertion and motivation of musical feedback during stair climbing therapy sessions, and,
(2) To determine if musical feedback would have an effect on the achievement of the goals of the therapy session.

*It was hypothesized that children would enjoy the musical stairs system which would lead to increased levels of motivation*\(^9\text{-}^{11}\). Stair-climbing goals generally focus on (a) increasing stability and decreasing the supports needed by a child to climb the stairs (e.g., use of therapist, handrails etc.), and (b) improving the step pattern used to climb the stairs. Typical step patterns range from non-reciprocal (i.e., two feet on one step) to reciprocal step (i.e., alternating the foot used to climb from left to right resulting in one foot on each step) movements. Encouraging reciprocal steps is a primary goal in many therapy sessions and was the focus of this study. Based on other interactive rehabilitation systems developed\(^{12\text{-}14}\), *it was hypothesized that by providing audio feedback on each reciprocal step, the achievement rate of this goal could be significantly increased.*

**Objective 2: System Design**

(1) To collect kinematic data associated with a range of gait patterns during stair climbing therapies,

(2) To develop an algorithm to detect the time of initial contact at which point the foot makes contact with the stair, and,

(3) To validate the accuracy of the developed algorithm on a second set of independent data.

Current research in using portable sensors to detect gait events is lacking not only with respect to analyzing stair climbing gait, but also pathological gait in young children. Based upon research on adults\(^{15\text{-}21}\), *it was hypothesized that an algorithm could be developed to detect gait events in our patient population with 90% accuracy.*

### 1.3 Thesis Layout

The thesis is presented as a compilation of two papers that taken together provide insight on the design of a musical stairs system that can detect stair climbing gait events, and provide auditory feedback and the impact of this system on physical therapy sessions. Since the papers are written independently, there will be some overlap in the introductory material provided in each. The
research is of interest to researchers, therapists and clinicians who are interested in creating fun and interactive environments for various gait therapy sessions or who are interested in analyzing stair climbing gait in children. The chapters following this introduction are:

- Chapter 2 investigates the impact of musical feedback on stair climbing therapy sessions. The effect on enjoyment, exertion and motivation was explored. One specific goal of stair climbing therapy, taking reciprocal steps, was investigated with respect to the effect of musical feedback on achievement of this goal.

- Chapter 3 presents the design of a wireless, portable musical stairs system that was used to collect kinematic data from children during stair climbing therapy sessions. An algorithm was developed to detect initial contact events from the kinematic data.

- Chapter 4 reiterates the contributions of this thesis project and lays out the direction for future research.
Chapter 2

2 The Impact of Musical Stairs on Stair-Climbing Physical Therapy for Children

2.1 Abstract

Stair-climbing is an important motor skill that is often a focus in pediatric rehabilitation. An interactive system was designed to provide audio feedback to children engaged in stair-climbing therapies in the form of animal sounds or piano chords. The purpose of this study was to investigate the impact of musical feedback on the achievement of a targeted therapeutic goal, namely, use of reciprocal steps. Stair-climbing therapy sessions conducted with and without the audio feedback were compared in a randomized AB study. Seventeen children, aged 4-7 years, with various diagnoses participated. The achievement rate of reciprocal steps was documented for each session. Self-reported and therapist-reported evaluations of perceived exertion, motivation, and enjoyment were collected. Additionally, a blinded physical therapist reviewed silent video recordings to provide an objective assessment of participants’ enjoyment, motivation, and exertion. Audio feedback resulted in a 5.7% increase (p=0.007) in reciprocal steps. Levels of participant enjoyment increased significantly (p=0.031) and motivation was reported to increase with audio feedback. No significant difference was noted in perceived exertion. In conclusion, these positive results indicate that the provision of audio feedback may influence the achievement of therapeutic goals and promote enjoyment and motivation in young patients engaged in rehabilitation therapies. This study lays the groundwork for future longitudinal research investigating the efficacy of audio feedback in stair-climbing and other rehabilitation therapies.

2.2 Introduction

The promotion of neuroplasticity is key to the success of rehabilitation therapies and effective motor learning. Neuroplasticity is fostered in an environment that provides: (i) opportunities for repeated practice of targeted tasks that slowly increase in complexity, (ii) immediate feedback in line with performance, (iii) motivation, and (iv) reward. Recent advancements in technology are resulting in unique opportunities to create therapy environments that are optimally designed for neuroplasticity. Virtual reality and biofeedback are two promising fields
of research wherein visual and auditory stimuli are used to create fun and interactive therapy environments\textsuperscript{1,10-11}.

\textit{Virtual Reality Therapy.} Harris et al.\textsuperscript{9} investigated the impact of VR environments on children’s motivation during therapeutic play. They discovered that playing in an interactive environment was motivating for the children, as determined by an observer-report questionnaire, and could be used as a successful tool to improve therapy outcomes. Corrêa et al.\textsuperscript{10} created a virtual musical system, where cards of various shapes, sizes, and colours would produce different musical sounds when the child interacted with them. The system was successfully demonstrated with a child with Cerebral Palsy (CP) in arm extension exercises. Pyk et al.\textsuperscript{11} developed interactive video games that utilized instrumented gloves to promote reaching and grasping tasks. Participants reported higher levels of exertion and motivation when using the interactive system versus their standard therapy sessions. As such, previous literature supports the hypothesis that interactive environments can motivate patients engaged in physical rehabilitation therapies which may lead to measureable improvements in the therapeutic outcomes\textsuperscript{3}.

\textit{Biofeedback.} Biofeedback in motor learning tasks involves the representation of an individual’s body movements in a form that they can use to modify and correct a particular motion\textsuperscript{23}. Audio biofeedback systems are suspected to improve the motor learning process\textsuperscript{24}, particularly when linked to specific therapeutic goals\textsuperscript{14,22,25}. Several studies support this hypothesis in walking and gait therapies. Schauer et al.\textsuperscript{12} found that musical feedback modulated by the participant’s gait, improved several parameters (e.g., stride length and symmetry deviation) in the patient’s walk when compared to conventional gait therapy. Hirokawa et al.\textsuperscript{13} developed a gait training tool that provided audio feedback relating to the length of the stance phase of gait, and observed less variability in temporal parameters of gait with their tool. Kassover et al.\textsuperscript{26} reported that providing auditory feedback on heel strike events improved dorsiflexion in patients with cerebral palsy. Auditory stimuli have also been shown to have a larger impact on gait dynamics than visual stimuli\textsuperscript{27}.

In this study, we will evaluate an audio feedback system to encourage and reward effective stair-climbing by children engaged in physical rehabilitation. Stair climbing goals generally focus on (1) increasing stability and decreasing the supports needed by a child to climb the stairs (e.g., use of therapist, handrails etc.), and (2) improving the step pattern used to climb the stairs. Typical
step patterns ranges from non-reciprocal (i.e., two feet on one step) to reciprocal step (i.e., alternating the foot used to climb from left to right resulting in one foot on each step) movements. In this study, we focused on the achievement of reciprocal steps.

The objectives of this study were (1) to determine the impact of musical feedback on enjoyment, exertion and motivation during stair climbing therapy sessions, and, (2) to determine if musical feedback would have an effect on the achievement of a therapeutic goal, namely, use of reciprocal steps. Based on previous works with interactive and audio biofeedback environments for physical therapy, it was hypothesized that the interactive ‘musical stairs’ would create an enjoyable therapy environment and lead to increased levels of motivation. By rewarding the achievement of a specific goal of the therapy, it was also hypothesized that the rate of achievement of that goal would be significantly increased when compared to typical therapy sessions.

2.3 Methods

2.3.1 Study Design

A randomized AB study design was adopted to compare (A) the control condition (i.e., standard stair-climbing physical therapy without audio feedback) and (B) the intervention (i.e., stair climbing therapy with audio feedback). Eight participants were randomly assigned to receive the control condition in the first session while the remaining 9 participants were exposed to the audio feedback during the first session.

2.3.2 Participants

Children practising stair climbing while undergoing physical therapy in the Integrated Educational Therapy program at Bloorview School Authority were recruited for this study. Children with known sensitivities (e.g., to sounds) that would make participation uncomfortable or dangerous and those that did not have typical or corrected to typical hearing were excluded from the study. A total of 17 children, aged 4-7 years (12 male, 5 female, mean age of 5.1 years [SD=1 year]) were recruited for the study with a variety of diagnoses as summarized in Table 1. Two physical therapist assistants (PTAs), who run the stair-climbing therapy sessions, were also recruited.
Diagnosis | Number of Participants
--- | ---
Cerebral Palsy, GMFCS Level 1 | 1
Cerebral Palsy, GMFCS Level 2 | 3
Cerebral Palsy, GMFCS Level 3 | 5
Gross Development Delay | 5
Gross Motor Delay | 1
Meningoencephalitis | 1
Neurofibromatosis | 1

Table 1 - Summary of participant diagnoses (n=17).

Ethics approval for this study was obtained from the research ethics boards at Holland Bloorview Kids Rehabilitation Hospital and the University of Toronto. Informed consent was obtained from the children’s parents and PTAs and assent was obtained from the child.

2.3.3 Data Collection Instruments

A custom software application was developed in Microsoft Visual C++ 2008 Express Edition (Microsoft Corp., Redmond, WA) to provide audio feedback on demand. The software was run on a laptop such that audio feedback could be manually triggered by the researcher when a successful stair-climbing event was observed. In this case, a successful stair-climbing event was defined as the accomplishment of a reciprocal step. This procedure, known as the Wizard of Oz technique, gives the illusion that a system is being controlled by a computer, when it is actually being controlled by an observer. It is beneficial in designing human-computer interfaces as it allows one to rapidly test an interface, and in this case test a hypothesis (i.e., that audio feedback can improve the achievement of a therapeutic goal), prior to dedicating considerable time and resources to the system development.

Video data were recorded using a Sony DCR-SR85 (Sony Corp., Tokyo, Japan) handheld digital camcorder at 30 fps. Self-reports of exertion and enjoyment were collected using the Pictorial Children’s Effort Rating Table (P-CERT) and Smileyometer scales respectively. The P-CERT consists of pictorials of a child at different effort levels on a set of inclining steps and has been validated for use with children aged 10-15 years (Appendix A). Note: there are no self-reported measures of perceived effort that have been validated specifically for the young age range of interest in this study. The Smileyometer scale is a set of five pictorial representations of a smiley face, depicting a range of feelings from awful to brilliant (Appendix A). It has been validated with children aged 7 to 13. Customized questionnaires (dichotomous Yes/No
questions) were used to obtain further insights from participants regarding the musical feedback system. The questionnaire responses were limited to dichotomous Yes/No responses due to the young age of the participants and variety of cognitive abilities. The PTA scored a customized questionnaire to provide an observer report of the child’s enjoyment, exertion, performance and motivation during the session (5-point Likert-type scale). Details for both questionnaires are presented in Table 2 and Table 3 (Appendix B and C). The questionnaires were specially designed to probe user enjoyment and motivation, system usability and desired areas for future development, and also to corroborate participant responses to the P-CERT and Smileyometer scales.

A second blinded observer report was conducted on the muted video recordings of the stair-climbing session. The blinded observer, who had no prior association with the study, was trained as a physiotherapist and had previous experience working with a similar paediatric population. This observer recorded the length of the therapy session, the time the child’s face was visible on camera and the time spent smiling. Smiling was defined to be any moment where the child’s expression indicated enjoyment and/or amusement with upward curving of the corners of the mouth. Reports of the child’s enjoyment, exertion, performance, motivation, fatigue and distraction were also collected using a customized questionnaire (5-point Likert-type scale). The questionnaire was specially designed to probe these measures and can be found in Appendix D. The blinded observer was provided with access to all session recordings to be analyzed over a span of three non-consecutive days.

<table>
<thead>
<tr>
<th>Participant Questionnaire</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Did you have fun climbing the stairs?</td>
</tr>
<tr>
<td>2. Do you feel tired?</td>
</tr>
<tr>
<td>3. Did the musical stairs make you want to climb the stairs?</td>
</tr>
<tr>
<td>4. Were the sounds too loud?</td>
</tr>
<tr>
<td>5. Did you like the sounds?</td>
</tr>
<tr>
<td>6. Were the sensors annoying to wear?</td>
</tr>
</tbody>
</table>

Table 2 - Details of the participant questionnaire. Responses were either Yes or No.
Physical Therapy Assistant Questionnaire

1. The child exerted themselves more on the musical stairs.
2. The child performed better on the musical stairs.
3. The child enjoyed the sound feedback from the musical stairs.
4. The child was more motivated on the musical stairs.

Table 3 - Details of the PTA questionnaire. Responses ranged from Strongly Agree to Strongly Disagree.

2.3.4 Study Protocol

Each participant was observed during two consecutive physical therapy sessions separated by at least 1 and no more than 3 weeks. Only the stair climbing portion of the therapy session was observed. The participants climbed up and down a single flight of stairs. The stairs were not designed specifically for therapy purposes and were located in the hospital stairwell. The session lasted between 1 to 5 minutes, depending upon the child’s abilities. At the start of the session, informed assent was obtained from the child. Informed consent was obtained previously from the parent and participating PTAs. For phase B (therapy with audio feedback), the child was given a choice between animal sounds or piano notes. Video recording was then begun. To realistically simulate the system interface, two wireless inertial sensors (22 grams, 53mm x 32mm x 25mm, Realtime Technologies Ltd., Dublin, Ireland) were attached to the participant’s shoes. Of note, the “placebo” sensor was attached in both the phase A and phase B conditions to ensure that the blinded observer was not able to distinguish between the two conditions from the muted video recordings. In line with the Wizard of Oz technique, the “placebo” sensor facilitated the illusion that the sensor system and not the researcher was triggering the feedback. For phase B, audio feedback was provided only when the child used reciprocal steps to climb the stairs (i.e., the targeted goal of the therapy session). The PTA provided their standard level of motivation and guidance for both phase A and B, which included providing physical support to the child as necessary and motivational cues to encourage stair climbing. Upon completion of the stair climbing portion of the therapy session, the sensors were removed from the participant and the therapy session continued as usual without further intervention.

For both phase A and phase B, the child was asked to fill out the P-CERT and Smileyometer scales at the completion of the session, with assistance from the researcher and PTA. For phase
B, the child and PTA were also asked to fill out the customized feedback questionnaires. The researcher and PTA assisted the child in understanding and responding to the questionnaire.

2.3.5 Data Analysis

The video recordings were analyzed to determine the total number of steps taken and the number of reciprocal steps taken during the therapy session. The number of reciprocal steps taken was the primary outcome measure used in the study. Descriptive statistics (e.g., medians, means) were used as appropriate to summarize measurement and questionnaire data. Percent reciprocal steps taken was compared between phase A and phase B using a repeated-measures ANOVA test, taking into account the effect of the order of presentation of audio feedback (i.e., those that received phase A in their first versus their second session). Percentage of time spent smiling was compared using a paired t-test. Ordinal data (i.e., P-CERT, Smileyometer, and blinded observer ratings) were also compared via a Wilcoxon test. Frequency counts and appropriate descriptive statistics were used to present data associated with the participant and PTA questionnaires.

2.4 Results

2.4.1 Therapeutic Goal: Reciprocal Steps

The average number of steps taken per stair climbing therapy session was 25 [SD=1.8]. An average of 83% [SD=8%] of these steps were made using a reciprocal step pattern without audio feedback compared to 89% [SD=9%] when audio feedback was provided. As such, a significant increase of 5.7% [SD=7%] in achievement of the therapeutic goal was observed with audio feedback (p=0.007). A summary of the results for each participant is shown in Figure 2. Of note, achievement of the therapeutic goal was enhanced or remained the same in 88% of the 16 participants compared. Those that received audio feedback in their first session had an average increase of reciprocal steps taken of 7.2% [SD=6%], and those who received feedback in their second session had an average increase of 4.3% [SD=8%]. However, this difference did not reach a level of statistical significance (p > 0.05). Due to technical difficulties with the camera, reciprocal step data were not available for one participant.
Figure 2 - A comparison of the reciprocal steps taken by each participant both with and without audio feedback. (/100) (n=16)

2.4.2 P-CERT and Smileyometer Scales

Given the young age of the children and, in some cases, cognitive challenges, only 11 participants were able to sufficiently understand and complete the P-CERT, while 12 were able to respond with the Smileyometer to indicate their level of enjoyment. Results for perceived exertion and enjoyment are presented in Figure 3 and Figure 4, respectively. The P-CERT scale ranged from 1 (very, very easy) to 10 (so hard I’m going to stop). For the Smileyometer scale, when participants were asked how much fun they had climbing the stairs, 1 represented “It was awful” and 5 represented “It was brilliant”. There was no significant difference in P-CERT scores between the session with no feedback and with audio feedback (p > 0.05). Median Smileyometer scores associated with enjoyment significantly increased by 1 [IQR=1.3] (on a 5-point scale) when audio feedback was provided as compared to sessions with no feedback (p=0.031).
Figure 3 - Summary of the P-CERT scores both with and without audio feedback. (/10) (n=11)

Figure 4 - Summary of the Smileyometer scores both with and without audio feedback. (/5) (n=12)

2.4.3 Questionnaires

Fifteen child participants were able to understand and answer the questionnaire providing feedback on the musical stairs. Of these participants, 100% reported having fun, 88% found the
audio feedback to be motivating, and 86% liked the feedback. Conversely, 36% of these participants reported that the feedback was too loud, 25% felt the sensors were not comfortable to wear, and 40% felt tired following the session.

The PTAs completed the questionnaire for all 17 participants and reported on the child’s exertion, performance, enjoyment and motivation during the therapy session with audio feedback. Responses ranged from Strongly Agree (1) to Strongly Disagree (5). The PTAs disagreed that the participants exerted themselves (4 [IQR=1]) and neither agreed nor disagreed that the participants performed better (3 [IQR=1]) when audio feedback was provided compared to standard therapy. However, they did agree that participants enjoyed the therapy session (2 [IQR=1]) and were more motivated when audio feedback was provided (2 [IQR=1]).

2.4.4 Blinded Video Analysis

Due to technical difficulties with the camera, video recordings of both sessions were recorded for only 16 of the 17 participants. Average values for the session duration, the percentage of time the participant’s face is visible on video, and the percentage of facial visibility during which the participant is smiling is presented in Table 4. An increase in smiling time was noted when comparing the feedback condition with the no feedback condition. However this did not reach a level of statistical significance with the sample size collected in this study (p = 0.074).

<table>
<thead>
<tr>
<th></th>
<th>Without Feedback</th>
<th>With Feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean (SD) Session Length (s)</td>
<td>143.7 (79)</td>
<td>144.3 (69)</td>
</tr>
<tr>
<td>Mean (SD) Time Face is on Camera (%)</td>
<td>52.9 (17)</td>
<td>56.0 (20)</td>
</tr>
<tr>
<td>Mean (SD) Time Smiling on Camera (%)</td>
<td>46.0 (28)</td>
<td>60.7 (30)</td>
</tr>
</tbody>
</table>

Table 4 - The average breakdown of the session time with respect to the time the participants face is visible on camera and the percentage of visible facial time the participant is smiling. (n=16)

Figure 5 provides the average ratings reported by the blinded assessor when evaluating the extent to which participants experienced the following during each therapy session: motivation, physical exertion, enjoyment, distraction, performance and fatigue. The rankings ranged from
Strongly Agree (1) to Strongly Disagree (5). No significant differences were observed in participant motivation, exertion, distraction, achievement of the therapeutic goal or fatigue between the sessions without feedback and those with audio feedback. A significant median increase of 0.5 [IQR=1] in participant enjoyment (p=0.02) (on a 5-point scale) was noted by the blinded observer when comparing the therapy session with audio feedback to that without.

**Figure 5 - The median ratings of the blinded observer.** A significant difference (p < 0.05) between no audio feedback and the presentation of audio feedback is indicated by (*). (n=16)
2.5 Discussion

2.5.1 Key Findings

This study investigated the impact of providing audio feedback to reward achievement of reciprocal steps during stair climbing therapies with children between the ages of 4 and 7 years. Key findings are as follows:

1. Achievement of the therapeutic goal was improved when audio feedback was provided. Specifically, a statistically significant 6% increase in reciprocal steps was observed.

2. All reports (child, therapist, and blinded observer) indicated increased levels of enjoyment during therapy sessions with the audio feedback. The child-report indicated a significant increase. While the blinded observer report did not reach a level of statistical significance, the percentage of time spent smiling was higher in therapy sessions conducted with the audio feedback (61%) compared to those without (46%).

3. Both child- and therapist-reports suggested that the musical stairs provided additional motivation during the therapy session. Increasing children’s motivation to actively participate in physical therapy sessions may boost attendance rates and provide a tool to support PTAs with their motivational cues. It may also lead to improved motor learning and achievement of therapeutic outcomes.

4. No differences in perceived exertion were noted.

5. The blinded assessor did not note any difference in the levels of distraction between the two feedback scenarios. Additionally, no significant difference in the duration of the therapy session was observed. These findings suggest that the audio feedback did not distract the children from the therapy task.

These results are in line with previous studies noting enhanced enjoyment and motivation when interactive environments are used in rehabilitation therapies\(^1\,2\,10\,11\).

2.5.2 Child, PTA, and Technology Interaction

Qualitatively, a number of interesting observations were noted with respect to the dynamic interaction between the child, the PTA, and the technology. Of note is the important role of the
PTA during therapy sessions. Audio feedback is not meant to replace the role of the PTA, rather it should augment it. The children often required considerable external motivation and persuasion to participate fully in the therapy sessions. As such, a large part of the PTA’s role is to provide motivation and encouragement to the children in an attempt to make the therapy session as fun as possible. It was observed that the PTAs quickly and naturally integrated the technology, aligning their motivational cues with the audio feedback, encouraging the child to listen to the sounds and promoting the use of reciprocal steps to generate audio feedback. The audio feedback also promoted social interaction between the PTA and participant, as they discussed what animals were making sounds or what song the child was playing. This increased social interaction may lead to a closer bond between the PTA and child over a long term basis.

2.5.3 Study Limitations

The following outlines a number of study limitations:

- The study design is unable to determine the clinical significance of a 6% increase in reciprocal steps. Repeated practice is an important component of the motor learning process, therefore it is hypothesized that over time, even a small increase in the rate of reciprocal steps might lead to improved outcomes. This has been observed on a short time scale with postural stability studies, where audio feedback reduced the time it took for participants to learn to balance themselves on an unstable platform\textsuperscript{14}. Nevertheless, longitudinal studies are needed to test this hypothesis and also the sustained level of enjoyment/motivation that the audio feedback can provide.

- It is noted that all participants were able to complete a large percentage of steps using the reciprocal step pattern. This may have been due to the fact that data collection took place towards the end of the school year after the children had been practicing stair climbing for a period of 9 months. A certain level of proficiency would be expected in achieving this goal at this stage, so any additional improvements with audio feedback would be expected to be incremental. Future studies are needed to evaluate the efficacy of audio feedback in children who are just beginning stair-climbing therapies.

- Therapy sessions took place in a building stairwell, with one PTA, two researchers and the participant on the stairs. Given the small area and the number of people on the stairs,
it proved difficult to consistently capture participants’ faces which were often obstructed by the PTA or looking down at the stairs. This may have decreased the accuracy of the “smile count” data.

- A Wizard of Oz technique was employed in this study to simulate an automated algorithm that would trigger audio feedback. As such, the results from this study are comparable to an automated system that performs flawlessly. Since we would expect any automated system to have some errors in determining when to provide feedback, it is not known what impact an imperfect system would have on our results.

This study focused on young children with varying cognitive abilities. While attempts were made to include only children who were able to sufficiently understand and respond to the feedback questionnaires, a number of the children were not able to respond to questions using ordinal or Likert-type scales. The inclusion of the PTA and the blinded observer’s assessments in addition to quantitative measures of goal achievement was intended to provide a more comprehensive picture from which conclusions can be based upon the agreement of the results.

2.5.4 Future Work

The next step will be to integrate an automated system to trigger audio feedback and to record quantitative metrics pertaining to gait dynamics. Of note, an alternative approach to an automated system is to simply provide therapists with the ability to trigger the sounds themselves. Advantages of this approach include: the provision of feedback that is well-aligned with the child’s performance as judged by an expert observer, the flexibility to provide or discontinue feedback quickly and intermittently throughout the therapy session as dictated by the child’s attention and context, and ease of implementation. Alternatively, advantages of an automated system include: minimal increase in cognitive load placed on the therapist and the ability to collect and monitor additional quantitative data regarding gait dynamics that could be used to inform physical therapists on patients’ progress and when modifications to a particular therapy routine is needed. The latter may be of particular relevance given the current shift towards clinical care models wherein a physical therapist will design and oversee the rehabilitation programs for a large number of patients, while a PTA will conduct the day-to-day therapy session. The additional quantitative data that the audio feedback system could provide
could be used to inform physical therapists on patients’ progress and when modifications to the therapy would be necessary.

Participant feedback indicated a number of important areas for future development of the system. For instance:

- Thirty-six percent of the children found the audio feedback to be too loud. The system must therefore be designed such that volume can be easily adjusted to accommodate individual preferences.

- Fourteen percent of the children did not like the feedback. While these children were not adverse to the idea of audio feedback, they desired different sound options (e.g., cars or more animals sounds than the ones provided). The eventual system must therefore include a more expansive sound library to accommodate individual preferences.

- Twenty-five percent of the children found the current sensor location at the heel of the shoe to be uncomfortable. For some participants, it was observed that while descending the stairs, the sensor would hit the stairs, as sometimes the foot would not be extended very far when coming down each step. To avoid this situation, different sensor locations (e.g., the front of the shoe on the laces) should be investigated in order to provide a more natural stair-climbing experience.

A number of areas for future work associated with the evaluation of the musical stairs system are also noted:

- The current study established the short term effects of musical feedback on stair-climbing therapy sessions. However, it is not known what the long term effects of this system will be. A longitudinal study using the system should be conducted in order to determine the best method of integrating audio feedback in stair-climbing therapy sessions. It is not known whether the effects of the feedback are a novelty effect, and if the benefits will subside once the novelty wears off. The presentation of feedback can also be studied, to determine if a fading frequency of feedback, where feedback is gradually reduced until feedback is no longer required, would achieve better results than providing a consistent level of feedback.
Two existing tools, the P-CERT and Smileyometer were used to obtain user-reported levels of exertion and enjoyment. Customized questionnaires were also created to obtain reports from the child and PTA regarding the impact of the technology on the therapy session. These various tools were used in a young paediatric population and demonstrated consistent results. However, in order to use these tools effectively in further research, their reliability and validity must first be established in a set of separate studies.

This study focused on the achievement of a single therapeutic goal. The impact of providing audio feedback associated with other goals is of interest in future studies as well. Besides the pattern of gait, therapists also work on the amount of support the child needs, working gradually from therapist and handrail support to independent stair-climbing. In order to require less support, the child needs sufficient strength and proper stair-climbing technique. Audio feedback could be provided to encourage correct stair-climbing technique. For example, feedback could be provided when the child leans forward to grab the handrail before climbing to the next step. Feedback could also be used to indicate when the child is not balanced or applying too much weight to one foot or the other. A measure of gait symmetry can also be used to trigger feedback.

The types and extent of audio feedback provided could be designed to evolve as the patient progresses through the rehabilitation program. As a precursor to stair-climbing and gait therapy, children first need to learn to shift their body weight from side to side. Audio feedback could be provided to reinforce this goal, especially in children who are in the early stages of their therapy program. As the child progresses and nears completion of their therapy program, melodies as opposed to sounds could be used to encourage smoother and faster movements. Methods to generate audio feedback for these goals, and standard gait therapy as well, should be investigated in order to extend the potential benefits found in this study.

2.6 Conclusion

The impact of providing musical feedback during stair-climbing therapies was investigated. Audio feedback was found to increase enjoyment and motivation during stair-climbing therapies without causing undue distraction. Audio feedback rewarding the desired therapeutic goal increased the percentage of reciprocal steps taken by 6%. Participant feedback revealed the following recommendations for improvement of the system: (1) provide adjustable volume controls, (2) expand the sound library, and (3) adjust the location of the sensors to the front of the
shoe. The promising results of this study lay the groundwork for the user-centered design of the musical stairs system and supports further research to investigate the long term effects of audio feedback in physical rehabilitation therapies.
Chapter 3

3 Real Time Detection of Pathological Gait Events during Stair Climbing in Children using Portable Sensors

3.1 Abstract

Stair-climbing is an important mobility skill for promoting independence and activities of daily life and is a key component of rehabilitation therapies for physically disabled children. The physical and cognitive effort to acquire this skill can be extremely challenging, frustrating, and arduous for children. This study describes the design of an interactive musical stairs system to increase motivation, to enhance enjoyment, and to provide immediate feedback to children engaged in stair-climbing therapies. The system uses inertial sensors to detect initial contact (IC) events each time a child makes a step. To develop the algorithm (Phase 1), kinematic data was collected from eighteen children, aged 4-6, with a range of stair-climbing abilities. Eight children aged 4-6 participated in Phase 2 of the study to test the algorithm. Using a single algorithm and parameter set for all participants, detection accuracy in Phase 1 was 87% [SD=9%], timing error was 0.25s [SD=0.2], and the false positive detection rate was 39% [SD=27%]. When the algorithm’s parameters were fine tuned for each individual, the detection accuracy was increased to 93% [SD=5%] and the false positive detection rate decreased to 12% [SD=9%]. In Phase 2, a semi-generalized approach was adopted in which three different parameter sets were established using data from Phase 1. Children were assigned to one of the three parameter sets based on an observable characteristic of their gait, their speed at climbing stairs. An accuracy of 96% [SD=3%], timing error of 0.23 s [SD=0.2s], and a false positive detection rate of 6% [SD=5%] was achieved in Phase 2. Future work will investigate the impact, if any, of IC event timing error on system usability and the impact of biofeedback and monitoring of kinematic data on therapeutic outcomes.

3.2 Introduction

Like level walking, stair-climbing is an important component of physiotherapies for individuals with physical disabilities. The ability to climb stairs safely may be the determining factor delaying an inpatient’s return home or to school; it is often a key factor in optimizing functional
independence and participation in activities of daily living. Effective motor learning hinges on a number of elements including repetition, motivation, enjoyment, and feedback. While therapists strive to provide an environment conducive to motor learning, the demands of supporting a child physically and emotionally, while monitoring movements and progress, can be quite onerous.

Recent advancements in technology are resulting in unique applications in the field of physical rehabilitation and the development of tools to support therapists and children engaged in motor learning tasks. Systems have been created that use visual and auditory stimuli to create fun and interactive therapy environments. These systems utilize techniques such as virtual reality and biofeedback to motivate the patient to perform the desired task and to reward efforts. In physiotherapies, biofeedback is a process where information regarding an individual’s body movement is measured and represented to the individual in a form that they can use to modify and correct a particular motion. For example, Schauer et al. developed a biofeedback system that utilized audio biofeedback to improve gait training in stroke patients by modulating music tempo based on the patient’s walking speed. This study concluded that gait outcomes were improved when musical feedback was used compared to conventional gait therapy. Similarly, Kassover et al. used audio biofeedback to improve dorsiflexion at heel strike in children with spastic diplegia. By providing a rewarding buzzing signal on heel strike, a significant increase in dorsiflexion at heel strike was observed.

The overall goal of this research is to design and evaluate a system that provides audio feedback to children during stair-climbing therapies. The simplest approach to achieve this goal would be to design a system where the attending physical therapist manually triggers feedback when the child performs the desired task. While effective, this method would add to the therapist’s cognitive load, potentially detracting from his/her ability to provide optimal physical support, motivational and instructional cues, and to carry out performance assessments. An automated system has an added advantage in that it can provide the therapist with quantitative data related to the child’s movements which may be used to inform physical therapy intervention approaches and strategies. This paper describes the development and validation of a step detection algorithm that will form the backbone of an automated musical stairs system. To this purpose, the specific objectives of this study were: (1) to collect kinematic data (i.e., acceleration and rotation of the feet) associated with a range of gait patterns during stair climbing therapies from which a real-
A time algorithm was developed that detects when the foot makes contact with the stairs (Phase 1), and, (2) to validate the accuracy of the developed algorithm on a second set of independent data (Phase 2).

A steering committee, consisting of physical therapists at Holland Bloorview Kids Rehabilitation Hospital, was formed to guide the design process. Several meetings were held with the steering committee and physical therapy sessions were observed as well. The key design requirements established were:

- A musical feedback system for stair climbing therapy sessions for young children would be beneficial to the hospital patient population
- Must be child-friendly and very easy to use
- Must work with up to two physical therapists assisting child on stairs
- Unobtrusive sensors may be attached to either child or therapist
- Stairs must be in an easily accessible location; currently stairs in the gym or the stairwell are used

Based on this design process, it was decided to create a portable musical stairs system for use in physical therapy sessions. Instead of instrumenting a single set of physical stairs, the portable system consisted of sensors that would be attached to the child as they climbed stairs. The sensors would determine when foot contact was made with the stairs in real time and relay this information to a nearby laptop that would provide audio feedback. The benefit of this approach over a physical set of stairs is that its use is not limited to any one location. The system can also be used for other gait therapy sessions as well and not just for the stair climbing component.

The fundamental component of the proposed system is the sensor used to detect initial contact (IC) events of the foot with the stairs. Typically, force-sensitive resistors (FSRs) in or on the shoe or force plates on the floor can be used for this purpose\(^\text{33-34}\). FSRs would be cumbersome to attach to the child and could introduce a tripping hazard. Force plates would not meet our design goal of a portable system. Alternatively, wireless accelerometer and gyroscope based systems have been used to study walking gait\(^\text{15-21}\). Local maxima and minima in acceleration data have
been used to determine IC events\textsuperscript{16,19,35}. Gait kinematics have been studied with these sensors attached to the lower trunk\textsuperscript{19,40-41}, shank\textsuperscript{16-17,42} and foot\textsuperscript{16-17,21}. However, these sensors have not been used to study stair climbing gait nor have they been used to study pathological gait in a paediatric population.

3.3 Methods

3.3.1 Instrumentation

Gait kinematic data were collected using the Shimmer Wireless Sensor Unit with the 9DoF daughterboard attached (Realtime Technologies Ltd., Dublin, Ireland). The sensor was used to transmit data from a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer at a rate of 100 Hz, in real time over Bluetooth\textsuperscript{®} to a laptop for further processing. Sensors were calibrated once prior to data collection. The accelerometer sensor was calibrated by measuring the static effect of gravity on both directions of each axis\textsuperscript{43}. The gyroscope sensor was calibrated using manufacturer supplied data. The calibration was periodically verified throughout the course of the study to ensure recalibration was not necessary. The sensor x-axis corresponded to the anterior-posterior axis, the y-axis to the medio-lateral axis and the z-axis to the longitudinal axis, as shown in Figure 6. A custom software application was developed in Microsoft Visual C++ 2008 Express Edition (Microsoft Corp., Redmond, WA) to facilitate data collection. Video data were recorded using a Microsoft LifeCam NX-6000 Webcam (Microsoft Corp., Redmond, WA) at 30 fps. Data collection software and webcam were both operating on the same laptop.

\textbf{Figure 6 - The orientation of the sensor coordinate system.}
### 3.3.2 Participants

Children practicing stair climbing as part of their physical therapy in the Integrated Educational Therapy program at the Bloorview School Authority were recruited. A total of 18 children, aged 4-6 years (13 male, 5 female, mean age of 4.6 years [SD= 0.6 years]) participated in the algorithm development phase (Phase 1). A total of 8 children, aged 4-6 years (5 male, 3 female, mean age of 5.1 years [SD=0.8 years]) were recruited for the evaluation phase (Phase 2). In both phases, participants had a wide range of conditions, summarized in Table 5, which resulted in a diverse sample representing a variety of gaits.

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>PHASE 1 (development) Number of Participants</th>
<th>PHASE 2 (evaluation) Number of Participants</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cerebral Palsy, GMFCS Level 1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Cerebral Palsy, GMFCS Level 2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Cerebral Palsy, GMFCS Level 3</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Congenital Glycosylation Disorder, Type 1A</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Global Development Delay</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Global Motor Delay</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Meningoencephalitis</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Middle Cerebral Artery Stroke</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Myelomeningocele</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Neurofibromatosis, Type 1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5 - Summary of participant diagnoses for Phase 1 and 2.

Ethics approval for this study was obtained from the research ethics boards at Holland Bloorview Kids Rehabilitation Hospital and the University of Toronto. Informed consent was obtained from the children’s parents and assent was obtained from each child.

### 3.3.3 Study Protocol

The protocol for Phase 1 and Phase 2 of the study was identical and is described in the following. Each participant was observed during one of their weekly scheduled physical therapy sessions. Only the stair climbing portion of the therapy session was observed. At the start of the session, informed assent was obtained from the child. Informed consent was obtained previously from the parent. To synchronize the video and sensor data, the sensor was accelerated and then
decelerated at a high rate while on video, creating an easily discernible marker in the acceleration and video data. The Shimmer sensors were then secured to the heels of the participant’s shoes, one for each foot. The participant was asked to stand still for approximately 5 seconds in order to collect stance phase orientation data. The physical therapist assistant then began the stair-climbing session which proceeded as usual. The child’s movements were captured on video and by the sensors. Upon completion of the stair climbing portion of the therapy session, the sensors were removed from the participant’s shoes.

3.3.4 Data Analysis

The video data were reviewed and timestamps for the synchronization event and IC events were recorded. These timestamps were used to mark IC events in the sensor data. IC events were labeled as either (a) progressive (i.e., advancement of the participant up or down the stairs) or (b) non-progressive (i.e., stepping movements that did not result in upward or downward progression, but rather were performed in place, such as the child stamping their foot in place). Raw sensor data were imported into MATLAB (MathWorks, Natick, MA) for further analyses. Accelerometer and gyroscope data were converted into units of g and °/s using the calibration data established prior to data collection. These data were then used to calculate quaternions, a number system used to describe the orientation of the sensor as per an existing algorithm described by Madgwick\textsuperscript{38}. The magnetometer data were not used in this study.

A novel method was developed to determine the swing angle of the foot in the sagittal plane, which will form the basis for the step detection algorithm. When the foot is at rest in the stance phase, the anterior-posterior axis with respect to the sensor frame of reference matches the anterior-posterior axis with respect to the body frame of reference. As the foot swings, the two axes are no longer aligned, as shown in Figure 7.
The orientation of the anterior-posterior axis in the body and sensor frames.

The orientation of the anterior-posterior axis with respect to the sensor frame of reference can be determined using equation (1), where $q$ is the orientation quaternion and $v$ is the vector describing the axis’ orientation. We can then determine the swing angle, $\theta_s$ of the foot in the sagittal plane by determining the angle between the longitudinal axis component of the vector $v$ and the component of vector $v$ in the transverse plane, as described in equation (2).

\[
\begin{bmatrix}
  v_x \\
  v_y \\
  v_z
\end{bmatrix} = \begin{bmatrix}
  q_0^2 + q_1^2 - q_2^2 - q_3^2 \\
  2(q_0 q_3 + q_1 q_2) \\
  2(q_1 q_3 - q_0 q_2)
\end{bmatrix} \quad (1)
\]

\[
\theta_s = \alpha \tan^{-1} \left( \frac{v_z}{\sqrt{v_x^2 + v_y^2}} \right) \quad (2)
\]

A rule-based algorithm was developed to estimate IC events. This strategy was chosen over alternative approaches that require temporal windows of data (such as classifiers) in order to
ensure real-time performance of the algorithm. Algorithms based on distinct and repetitive patterns of temporal features such as toe-off, swing and heel strike were also not considered due to the extreme variability of pathological gait and their sensitivity to false positive detections. The following algorithm was thus designed:

a) Determine the stance phase orientation of the sensor for the stationary, standing participant prior to stair climbing.

b) Search for a local minimum in the longitudinal acceleration axis below a threshold level $A_t$. This will indicate a possible IC event.

c) After $t_a$ seconds, determine if the swing angle, $\theta_s$, matches the stance phase angle, within a tolerance level $S_t$. Search for the swing angle until $t_b$ seconds have expired. This will indicate whether the foot is in the stance phase.

d) In a $w$ second search window prior to c), check if the swing angle, $\theta_s$, was greater than the stance phase angle tolerance level $S_t$. This will indicate if the foot was swung back before the IC event.

e) If these conditions are met, then the time when the swing angle, $\theta_s$, matches the stance phase angle is considered an IC event. However, if the potential IC event occurs less than $P_{\text{min}}$ seconds (the minimum step period) after the last IC event, then it is not considered to be an IC event.

Data from Phase 1 were used to establish (a) generalized (based on all participants), (b) individualized (fine-tuned to each participant), and (c) semi-generalized detection algorithms. Data from Phase 2 was used to evaluate the performance of the generalized and semi-generalized algorithms.

**Generalized Algorithm.** Data from Phase 1 were used to determine appropriate values for the algorithm’s parameters, namely, $A_t$, $t_a$, $t_b$, $S_t$, and $w$. The value of $A_t$ was the most important parameter in detecting IC events. The remaining parameters were used to minimize the number of false positive IC events detected, and were dependent upon the value of $A_t$. As such, this reduced the complexity of defining the parameter set to a single variable optimization problem. Trial and error was used to determine the value of $A_t$ that maximized IC event detection accuracy to at least 90% across all participants. The values of $A_t$, $t_a$, $t_b$, $S_t$, and $w$ for the generalized algorithm were 0.2 g, 0.2 s, 0.2 s, 10°, and 1.17 s respectively. The parameter $P_{\text{min}}$ was set as 1.2 s, based upon the minimum step period calculated from all steps observed in Phase 1. The
The performance of the algorithm was recorded for two scenarios wherein: (i) only progressive IC events were considered to be true IC events and the detection of non-progressive IC events contributed to the false positive error rate, and (ii) both progressive and non-progressive IC events were considered to be true IC events. The absolute timing error, defined as the time difference between the observed IC event and the calculated IC event, was also calculated.

**Individualized Algorithm.** The five algorithm parameters were then tuned for each participant individually and optimized for high detection accuracy and low number of false positives. The performance of the individualized algorithms was calculated and recorded. Significant differences from the generalized algorithm were determined using a binomial test with Bonferroni adjustment. Video data were reviewed to determine why the algorithm (i) failed to detect or (ii) falsely detected an IC event.

**Semi-generalized Algorithm.** The parameters associated with the individualized algorithms were used to establish three sets of parameters, $P_1$, $P_2$, and $P_3$. Participants in Phase 2 were then assigned to one of these parameter sets based on the length of time taken to climb up and down the stairs. Participants were assigned to $P_1$ if their session time was longer than 200 s, $P_2$ if their session time was between 100 s – 200 s and $P_3$ if their session time was less than 100 s. The detection accuracy, number of false positives, and the timing errors were recorded for both the semi-generalized approach and the generalized algorithm. Significant differences from the generalized algorithm were determined using a binomial test with Bonferroni adjustment. The semi-generalized approach was adopted to maximize the performance of the algorithm while taking into account the wide diversity in gait characteristics associated with the diverse population. Video data were reviewed to better understand the cause of errors in IC detection.

Lastly, the impact of age and gender on IC detection accuracy was determined using the Pearson product-moment correlation coefficient and an unpaired t-test respectively. Due to the low sample size of each diagnostic group, the impact of the participant’s diagnosis on accuracy could not be determined. The performance of the algorithm (accuracy, timing error and false positive detection rate) was compared between stair ascent and descent using a paired t-test.
3.4 Results

3.4.1 Phase 1

3.4.1.1 IC Event Detection Accuracy

The results of the IC detection algorithm are summarized in Table 6. Results are presented for both the generalized and individualized algorithms and for the detection of (i) progressive IC events only, and, (ii) all IC events (progressive and non-progressive combined). No significant correlation was found between age and IC detection accuracy (p > 0.05) nor was a significant difference in accuracy found between genders (p > 0.05).

<table>
<thead>
<tr>
<th>Algorithm Parameters</th>
<th>IC Types</th>
<th>Number of IC Events</th>
<th>Detection Accuracy (SD) (%)</th>
<th>Timing Error (SD) (s)</th>
<th>Incorrect IC Events (SD) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalized</td>
<td>Progressive only</td>
<td>894</td>
<td>86.8 (9)</td>
<td>0.25 (0.2)</td>
<td>39.1 (27)</td>
</tr>
<tr>
<td>Generalized</td>
<td>Progressive and non-progressive</td>
<td>1114</td>
<td>88.1 (10)</td>
<td>0.25 (0.2)</td>
<td>13.6 (10)</td>
</tr>
<tr>
<td>Individualized</td>
<td>Progressive only</td>
<td>894</td>
<td>91.1 (5)*</td>
<td>0.25 (0.2)</td>
<td>36.9 (21)*</td>
</tr>
<tr>
<td>Individualized</td>
<td>Progressive and non-progressive</td>
<td>1114</td>
<td>92.6 (5)*</td>
<td>0.25 (0.2)</td>
<td>11.9 (9)</td>
</tr>
</tbody>
</table>

Table 6 - Summary of results for the IC detection algorithm. A (*) indicates a significant (p < 0.025) change when comparing generalized to individualized algorithms. (n=18)

Figure 8 to Figure 10 presents the IC detection accuracy, the timing errors, and the percentage of false positive IC events detected for each individual participant in Phase 1. In Figure 10, participant P1-2 had a particularly high rate of false positives. Of note, this participant had significant pathological gait and required considerable assistance in stair-climbing.
Figure 8 - IC event detection accuracy across four algorithm scenarios, both generalized and individualized, considering both progressive (P) and non-progressive (NP) steps. (n=18)

Figure 9 - IC event absolute timing error across four algorithm scenarios, both generalized and individualized, considering both progressive (P) and non-progressive (NP) steps. Of note, a mixture of lags (44%) and leads (56%) in timing error were observed. (n=18)
Figure 10 - Percentage of false positives across four algorithm scenarios, both generalized and individualized, considering both progressive (P) and non-progressive (NP) steps. (n=18)

3.4.1.2 Reasons for Algorithm Errors

To explore the performance of the algorithms in greater detail, video analysis was used to identify potential reasons for detection errors (i.e., false positives and false negatives). In order of decreasing frequency, IC events were missed when: (i) the foot exhibited an unusually small swing back before making contact with the ground (49% of false negatives), (ii) the foot did not return to the stance phase angle when contact with the ground was made (29%), (iii) the foot made contact with the ground with insufficient force to generate a detectable acceleration value (18%), and (iv) consecutive IC events occurred less than $P_{\text{min}}$ seconds apart (8% of false negatives). The algorithm falsely identified IC events when: (i) the heel of the foot was notably lifted off the ground, while the toe remained in contact (53% of false positive detections), or (ii) the foot was lifted off the ground and momentarily suspended in mid-air presenting a deceleration that is misinterpreted as an IC event (47% of false positive detections). Of note, no significant difference in overall accuracy was observed between stair ascent and descent. However, the average false positive detection rate was significantly higher during stair descent.
by 9% [SD=10%] (p=0.003), and average timing error was significantly longer during stair descent by 0.05s [SD=0.07s] (p=0.014).

3.4.1.3 Algorithm Parameters

The variation in the parameters used in the individualized algorithms (Table 7) associated with each participant was explored in greater depth.

<table>
<thead>
<tr>
<th>Participant</th>
<th>$A_t$ (g)</th>
<th>$t_a$ (s)</th>
<th>$t_b$ (s)</th>
<th>$S_t$ (°)</th>
<th>$W$ (s)</th>
<th>$P_{min}$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1-1</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>0.9</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-2</td>
<td>-0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>P1-3</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-4</td>
<td>0.1</td>
<td>0.2</td>
<td>0.4</td>
<td>15</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-5</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>15</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-6</td>
<td>0.5</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-7</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>15</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-8</td>
<td>0.5</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-9</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-10</td>
<td>0.1</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-11</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-12</td>
<td>0.7</td>
<td>0.2</td>
<td>0.2</td>
<td>15</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-13</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-14</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-15</td>
<td>0.3</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-16</td>
<td>0.2</td>
<td>0.2</td>
<td>0.3</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-17</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>P1-18</td>
<td>0.5</td>
<td>0.2</td>
<td>0.2</td>
<td>10</td>
<td>1.5</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Table 7 - Algorithm parameters used for each participant. (n=18)

From Table 7, it was observed that the variation in algorithm parameters was relatively small with the exception of $A_t$ (i.e., the acceleration threshold). Based on this observation, a semi-generalized approach was developed based on three parameter sets that differed only in their value of $A_t$. $A_t$ was set at 0g, 0.2g, and 0.5g in each of the three parameter sets respectively. Mode values were used to define the remaining parameters as follows: $t_a$=0.2s, $t_b$=0.2s, $S_t$=10°, $W$=1.17s, and $P_{min} = 1.2$. 
3.4.2  Phase 2

3.4.2.1  IC Event Detection Accuracy

In Phase 2, the performance of the developed algorithms was evaluated on an independent data set. Results are presented in Table 8 for both the generalized and individualized algorithms and for the detection of (i) progressive IC events only, and, (ii) all IC events (progressive and non-progressive combined).

<table>
<thead>
<tr>
<th>Algorithm Parameter Set</th>
<th>IC Types</th>
<th>Number of IC Events</th>
<th>Detection Accuracy (SD) (%)</th>
<th>Timing Error (SD) (s)</th>
<th>Incorrect IC Events (SD) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generalized</td>
<td>Progressive</td>
<td>328</td>
<td>93.4 (4)</td>
<td>0.24 (0.2)</td>
<td>37.3 (41)</td>
</tr>
<tr>
<td>Generalized</td>
<td>All</td>
<td>444</td>
<td>94.9 (3)</td>
<td>0.23 (0.2)</td>
<td>6.5 (6)</td>
</tr>
<tr>
<td>Semi-generalized</td>
<td>Progressive</td>
<td>328</td>
<td>94.3 (6)</td>
<td>0.25 (0.2)</td>
<td>36 (36)*</td>
</tr>
<tr>
<td>Semi-generalized</td>
<td>All</td>
<td>444</td>
<td>96.1 (3)*</td>
<td>0.23 (0.2)</td>
<td>6.2 (5)</td>
</tr>
</tbody>
</table>

Table 8 - Summary of results for the IC detection algorithm on Phase 2 data. A (*) indicates a significant (p < 0.025) change when comparing generalized to semi-generalized algorithms. (n=8)

Figure 11 to Figure 13 presents the IC detection accuracy, the timing errors, and the percentage of false positive IC events detected for each individual participant in Phase 2.
Figure 11 - IC event detection accuracy across four parameter sets in Phase 2, both generalized and semi-generalized, considering both progressive (P) and non-progressive (NP) steps. (n=8)

Figure 12 – IC event absolute timing error across four algorithm scenarios in Phase 2, both generalized and semi-generalized, considering both progressive (P) and non-progressive (NP) steps. Of note, a mixture of lags (46%) and leads (54%) in timing error were observed. (n=8)
Figure 13 - Percentage of false positives across four algorithm scenarios in Phase 2, both generalized and semi-generalized, considering both progressive (P) and non-progressive (NP) steps. (n=8)

3.4.2.2 Reasons for Algorithm Errors

As in Phase 1, video analysis was used to identify potential reasons for detection errors (i.e., false positives and false negatives). In order of decreasing frequency, IC events were missed when: (i) the foot made contact with the ground with insufficient force to generate a detectable acceleration value (48% of false negatives), (ii) the foot exhibited an unusually small swing back before making contact with the ground (22%), (iii) consecutive IC events occurred less than $P_{min}$ seconds apart (17%), and (iv) the foot did not return to the stance phase angle when contact with the ground was made (13% of false negatives). The algorithm falsely identified IC events when: (i) the heel of the foot was notably lifted off the ground, while the toe remained in contact (63% of false positive detections), or (ii) the foot was lifted off the ground and momentarily suspended in mid-air presenting a deceleration that is misinterpreted as an IC event (37% of false positive detections). Of note, no significant difference in accuracy, timing error or false positive detection rate was observed between stair ascent and descent ($p > 0.05$).
3.5 Discussion

3.5.1 Key Findings

A novel method to detect IC events during stair climbing in a paediatric population with a variety of pathological gaits was developed. A generalized algorithm with a single set of parameters to accommodate all participants yielded an accuracy of 88% [SD=10%] on training data, below the targeted accuracy of 90%. Accuracy was significantly improved by adopting an individualized algorithm, resulting in an accuracy of 93% [SD=5%] (p = 0.00). Testing the generalized algorithm on independent data resulted in an accuracy of 95% [SD=3%]. Accuracy was again significantly improved by adopting a semi-generalized approach which achieved a detection accuracy of 96% [SD=3%] (p = 0.02). The false detection rate for this algorithm was 6% [SD=5%] when all contact events were considered and 36% [SD=36%] when only progressive stair-climbing events were included. As expected, performance of the algorithm was significantly improved when the algorithm was customized to each individual. In practice, individualized algorithms could be established by requiring the user to first perform a trial run, where data is collected and each parameter set to optimize performance. While this may be a necessary step for individuals with extremely atypical gaits, the semi-generalized approach would be preferable as it would allow therapists to categorize the user by easily observed characteristics of their gait without the need for additional set-up. It would also be more robust to the progressive change in abilities and gait that might be expected over the course of rehabilitation.

3.5.2 Strengths and Limitations

In this study, we used wearable inertial sensors to detect movements of a diverse group of children with mobility challenges as they ascended and descended stairs. This approach is associated with a number of strengths:

- The system is portable, allowing therapists to use the system with any stairs they desire as opposed to limiting them to a single set of instrumented stairs. There is also the potential for the system to be used in environments outside of the clinical setting (i.e., at home).

- The sensors were easy to attach and non-intrusive. The heel of the shoe provided a fairly rigid and stable surface for sensor attachment. The IC detection algorithm was designed
to tolerate imprecise attachment of the sensor, so the therapist does not have to ensure the sensor is attached at an exact point or orientation each time.

- The system does not have a lengthy setup time nor does it require frequent calibration. The sensors were calibrated once and used for the duration of the study. The algorithm is robust enough to handle any slight deviation expected in the calibration due to temperature fluctuations.

- The design can be transferred to different sensor and computing platforms. Although the system was designed using the Shimmer sensor platform, the underlying sensors used, accelerometers and gyroscopes, are fairly ubiquitous, so any device incorporating these sensors could potentially be used. The current design requires a laptop to run the IC detection algorithm. However, the software can be ported to run on other portable devices as well, such as smart phones and tablets. The orientation algorithm used in the system requires significantly fewer computations than Kalman filter based orientation algorithms that are typically used. This allows the algorithm to run in real time on devices with reduced processing capabilities when compared to a laptop.

- The system was designed and evaluated with the target population. Very few studies have investigated inertial motion tracking in a paediatric population demonstrating such a diversity of pathological gait characteristics.

Limitations in the detection algorithm are as follows:

- While the algorithm accurately detects IC events, it is not able to reliably distinguish a stair climbing IC event from a non-stair climbing IC event. Variability in the accuracy and false positives detected are a result of the wide variety of gait patterns observed. Gait patterns that were more pathological resulted in reduced accuracy and/or increased detection of false positives.

- The average error in IC detection time in Phase 1 and 2 were 0.25 s and 0.23 s respectively. Compared to other studies using inertial sensors, a typical error value of 0.011 s could be expected. In this study, we used video as our standard for marking IC times instead of FSRs attached to the sole of the shoe as in other studies. FSRs were not
used in order to minimize potential tripping hazards and inconvenience to the participants. However, the use of video analysis likely decreases the accuracy of our timing error calculations. The video was recorded at 30 fps, which would also add up to 0.033 s of error to our IC time errors. Previous research in audio feedback for haptic interfaces has shown that a delay of 24 ms would be just noticeable. As such, it is likely that a delay would be perceived by users if this algorithm was incorporated into a musical feedback device for stair climbing. Improving the speed of detection and evaluating its effect on the user experience is therefore an important area for future work.

- The variety in gait patterns resulted in a number of errors. While the sensitivity of the algorithm could be increased in order to detect more true IC events, this would be accompanied by an increased rate of false detections. As such, a balance was struck in determining algorithm parameters that maximized accuracy while minimizing the number of false positives. The accuracy of the detection algorithm could be further improved if we could track the absolute position of the foot and not just the orientation. For example, Yun et al. used similar inertial sensors and methods to track the location of users indoors. They obtained an estimate of the absolute position of the foot by double integrating its acceleration. This would usually lead to an uncontrolled accumulation of error, known as drift, however they exploited the fact that the foot is stationary during the stance phase, so velocity can be updated to zero at these instances. Their method works well when the interval between corrections is sufficiently small. However, in our population, the time between subsequent steps is extremely variable and is relatively long when compared to typical adult gait. As such, integrating accelerometer data is not a viable option to determine sensor position.

- The IC detection algorithm was developed to accommodate a variety of gait patterns. While this provides opportunities for more widespread use, there are certain pathological gaits that will not be captured well by this algorithm. For example, the algorithm was least accurate for participant P1-7 (accuracy of 81% and a false positive detection rate of 30%) whose gait was very slow and unstable and required significant therapist and railing support to climb the stairs. As such, it may be necessary to develop more customized algorithms to specifically handle these types of pathological gait patterns. It would also
be interesting to study the minimum acceptable detection accuracy above which the user experience is not diminished.

3.5.3 Future Work

The overall goal of this research is to integrate the detection algorithms developed in this study into a system that provides musical feedback during stair climbing and gait therapies. To better distinguish progressive from non-progressive IC events, future efforts may engage the use of a third sensor attached to the child’s back. We would expect that progressive IC events would result in significant movement of the torso in contrast to non-progressive IC events. The additional biomechanical information obtained from inertial data recorded at the torso might also have clinical value for tracking a child’s progress with respect to balance for instance.

Future work must also focus on evaluating the overall system efficacy and the impact of providing automated audio feedback on the child’s enjoyment of therapy sessions and their achievement of therapeutic goals. More accurate measurement of the timing error, minimizing the timing error, and evaluating its impact on the user experience are also areas of future work.

The kinematic data collected by the sensors may also contain valuable clinical information that could be used by therapists to track progress within and across therapy sessions. It is possible that this information could be used to better inform physical therapy intervention approaches and strategies. However, in order to be useful, a method of interpreting the data and translating it into useful information that can be presented to the therapist will need to be developed. The expansion of the system for use in other therapies where a desired motion (e.g., heel strikes, balance) can be rewarded with audio feedback is also possible and will be a focus of future work.

3.6 Conclusion

An algorithm based on inertial sensors was developed to detect IC events of children with mobility challenges as they ascend and descend stairs as part of their rehabilitation therapy. While optimal performance is achieved when the algorithm’s parameters are fine-tuned to each individual, a semi-generalized approach was developed that is capable of accommodating a wide variety of gait patterns while providing acceptable accuracy rates. Future studies will focus on improving the system’s ability to distinguish between progressive and non-progressive IC events and decreasing the time required for detection.
Chapter 4

4 Conclusion

4.1 Summary of Contributions

The research presented in this thesis contributes the following to the field of paediatric rehabilitation:

1. The positive impact of providing audio feedback during stair-climbing physical therapies was established. Audio feedback was found to increase children’s motivation and enjoyment, while increasing achievement of the therapeutic goal to which it was linked.

2. Questionnaires were developed to elicit a report on the children’s experience with the musical stairs system. With further development and validation, these questionnaires could be used in other studies where children’s experience with technologies related to physical therapies needs to be analyzed, as no such tool to measure this exists.

3. An interactive musical stairs system for use in stair-climbing physical therapy sessions was designed and developed. A user-centered design process was followed that engaged both therapists and children participating in stair climbing therapy to outline important user requirements and design priorities.

4. A novel algorithm to detect IC events in pathological gait in a paediatric population while stair-climbing was developed. Three parameter sets were defined for use with a semi-generalized algorithm in order to accommodate a wide variety of gait patterns. Although the algorithm can successfully detect IC events, it cannot reliably distinguish between progressive and non-progressive stair-climbing IC events.

4.2 Directions for Future Research

This thesis is the first investigation of the use of musical stairs for stair-climbing physical therapy sessions. While several conclusions have been made, opportunities for further research have also been identified. These include:
• Investigating the use of additional sensors or other techniques to distinguish between progressive and non-progressive stair-climbing IC events.

• Determining the impact of timing error of IC event detection on the user experience. Of note, in this study, audio feedback was presented with little to no perceptible delay.

• Developing an informative and useful interface for the kinematic data collected during stair-climbing therapy sessions. A participatory design approach should be employed to determine the best way to interpret and present gait information to therapists. These kinematic data may be useful for planning and evaluating physical therapy interventions.

• Conducting a longitudinal study to determine the long term effects of audio feedback on stair-climbing physical therapies. The findings of this thesis may be valid for only a short time period. Once the novelty wears off, different strategies of presenting audio feedback may need to be developed to maintain enjoyment, motivation and performance levels.

• Using audio feedback with other goals of stair-climbing therapy. Only one important goal of stair-climbing therapy was investigated, taking reciprocal steps. Besides step pattern, therapists also work on reducing the amount of support the child needs while climbing the stairs. Learning proper stair-climbing techniques can reduce children’s need for external support. The impact of providing audio feedback when using proper technique, such as leaning forward to grab the handrail, maintaining balance, or maintaining symmetric gait can be investigated.

• Expanding the system to standard gait therapy. Stair-climbing therapy was focused on due to the challenging and important nature of this activity. However, there is no limitation on the system that restricts its use for standard gait therapy sessions as well. The effective use of an interactive musical system for standard gait therapies can be investigated with respect to specific therapeutic goals (e.g., minimizing “toe walking”).

4.3 Closing Remarks

Stair-climbing is a challenging activity for young children of varying abilities to master. Physical therapists utilize a range of techniques to motivate and encourage children to reach their stair-climbing goals. The aim of this thesis was to explore the impact of audio feedback on children’s
enjoyment, motivation, and achievement during stair-climbing therapies and to design an interactive musical stairs system to improve stair-climbing physical therapy sessions. The data collected showed that audio feedback increased levels of enjoyment and motivation, and led to increased achievement of a therapeutic goal (i.e., use of reciprocal steps).

While the data may show that the children enjoyed therapy with audio feedback, what is not shown is the diverse range of emotional reactions, from subtle smiles to full blown laughter and the sense of wonder as the children create a musical soundscape around themselves. Some participants were non-verbal, and I was not expecting much of a reaction with the audio feedback. However, when I witnessed their eyes light up when the sounds started playing, I knew audio feedback would have a positive impact without looking at any of the data. From what I experienced, interactive technologies used in a therapeutic setting have the potential to blur the line between therapy and play, resulting in a profound impact, not only on the goals of therapy itself, but on the child’s perception of what therapy is.
References


Appendices

A. PCERT and Smileyometer Scales
B. Participant Questionnaire

Please help us improve the musical stairs by answering these quick questions!

1. I had fun climbing the stairs.

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2. I feel tired.

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3. The musical stairs made me want to climb the stairs.

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4. I enjoyed being able to pick the type of sounds used.

<table>
<thead>
<tr>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
5. There were enough sound choices.

Yes | No
--- | ---

6. The sounds were too loud.

Yes | No
--- | ---

7. I liked the sounds.

Yes | No
--- | ---

8. The sensors were annoying to wear.

Yes | No
--- | ---

9. Are there any other sounds you would like added?
C. Physical Therapy Assistant (PTA) Questionnaire

Please help us improve the musical stairs by answering these quick questions!

1. The child exerted themselves more on the musical stairs.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>

2. The child performed better on the musical stairs.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>

3. The child enjoyed the sound feedback from the musical stairs.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>

4. The child was more motivated on the musical stairs.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
</table>
D. Blinded Video Analysis Form

Participant ID: __________________________

Session: 1 2

Length of session (in seconds): __________________________

Time spent smiling (in seconds): __________________________

<table>
<thead>
<tr>
<th>Time face is visible on video (in seconds):</th>
<th></th>
</tr>
</thead>
</table>

The child was engaged/motivated during the session

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The child exerted themselves to the best of their ability

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The child enjoyed the therapy session

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The child was distracted during the therapy session

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
One of the goals of the therapy session was to take alternating steps.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

This goal was met.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The child was fatigued by the therapy session.

<table>
<thead>
<tr>
<th>Strongly Agree</th>
<th>Agree</th>
<th>Neither Agree or Disagree</th>
<th>Disagree</th>
<th>Strongly Disagree</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Additional comments regarding the therapy session:

---

---