Human Factors in Healthcare 3 (2023) 100044

Contents lists available at ScienceDirect

Human Factors in Healthcare

journal homepage: www.elsevier.com/locate/hfh

Stepping Beyond Efficacy: Understanding the User Experience of Wearables for Children with Idiopathic Toe Walking in the Natural Setting

LouAnne Boyd [a,*], Rahul Soangra [b], Lara Mukhar [b], Rachel Kling [b], Marybeth Grant Beuttler [c]

[a] Chapman University, One University Drive, Orange, CA 92866
[b] Chapman University, 9401 Jeronimo Rd., Irvine, CA. 92618
[c] Oregon Institute of Technology, 3201 Campus Dr. Klamath Falls, OR 97601

A R T I C L E I N F O

Keywords:
Usability
acceptability
idiopathic toe walking
motor re-learning
wearable assistive technology
home environment

A B S T R A C T

Idiopathic Toe Walking is an atypical gait pattern that results in limited mobility, pain, and higher risk of falling. Current therapeutic interventions lack the ability to be implemented outside the clinic or lab. Beyond this, it is unclear if gait analysis and real-time feedback is technologically feasible to attain within a user's natural environment. In our research we aimed to understand the child and parent participants' experience of an innovative wearable system. We surveyed children and parents after the deployment of a functional prototype with real time vibrotactile feedback for awareness of toe walking via a shoe insert paired with a smartphone for visual feedback. Findings revealed insights into design considerations for wearable technologies for children. Factors such as comfort of using the system (physically and psychologically), child's perception and response to the vibrotactile feedback, and children and parents' perception of reduced fall risk, pain, and stigma are discussed.

1. Introduction

Toe walking is a gait pattern characterized by toe to toe initial contact. Toe walking can be observed in individuals with cerebral palsy, autism spectrum disorders, and several other medical conditions (Pomarino et al., 2016; van Bemmel et al., 2014; Williams et al., 2010). When toe walking is observed in an individual without an additional developmental, neurological, or neuromuscular condition, it can be classified as idiopathic toe walking. While the cause of idiopathic toe walking has not been established, limitations in balance (De Oliveira et al., 2021; Soangra et al., 2021; Williams et al., 2014), decreased function (De Oliveira et al., 2021; Shulman et al., 1997; Williams et al., 2014), increased incidence of pain (Fox et al., 2006; Pelykh et al., 2014; Rossi et al., 2018; Sobel et al., 1997), and lower quality of life scores (Caserta et al., 2022) indicate a need for intervention. Idiopathic toe walking is frequently observed early in life (Babb & Carlson, 2008; E Pistilli et al., 2014; Oetgen & Peden, 2012) and becomes a well-established pattern when treatment is delayed. Thus, intervention at an early age may decrease limitations in balance and function, as well as eliminate pain. By function we mean the ability to participate in age appropriate tasks and access their community safely, for example, ambulation over a variety of terrains and negotiating stairs. Effective treatment can be a challenge due to the complexity of an idiopathic toe walking diagnosis and varied treatment approaches. Parents have reported feeling helpless in knowing what course of action will be best for their child (Williams et al., 2020). This helplessness is understandable given the array of clinical methods to address idiopathic toe walking including, but not limited to physical therapy, casting, orthoses, and surgery in severe cases. All these intervention methods focus on 2 goals: 1) increasing limited dorsiflexion range of motion, and/or, 2) restraining active movement into plantarflexion during gait. Both these intervention goals presume that limited ankle mobility results in toe walking. The literature suggests that effects of these interventions tend to fade over time, requiring repeated bouts of treatment (Stricker & Angulo, 1998; van Kuijk et al., 2014; Westberry et al., 2021). Thus, there is an opportunity to find new and different treatments.

Recently, evidence for a different intervention strategy, motor re-learning, has emerged (Fanchiang et al., 2016; Williams and Curtin, 2010, 2016). Motor re-learning supports intervention that focuses on external feedback to increase heel strike repetition, which improves the learner's ability to learn to produce a typical, efficient heel strike (Conrad & Bleck, 1980; Marcus et al., 2010; Pelykh et al., 2014; Sanger,

* Corresponding author: LouAnne Boyd, Chapman University, One University Drive, Orange, CA 92866
E-mail addresses: lboyd@chapman.edu (L. Boyd), soangra@chapman.edu (R. Soangra), lmukhar@chapman.edu (L. Mukhar), rakling@chapman.edu (R. Kling), marybeth.grantbeuttler@oit.edu (M. Grant Beuttler).

https://doi.org/10.1016/j.hfh.2023.100044
Received 29 July 2022; Received in revised form 11 January 2023; Accepted 2 May 2023
Available online 4 May 2023

2004). To date, external feedback has consisted of providing augmented feedback through auditory information such as ring, buzzing or squeaking sound (Conrad & Bleck, 1980; Marcus et al., 2010) and through visual feedback such as the visualization of a footprint on a display (Pelykh et al., 2014). All these studies reported increased heel strike frequency over multiple days and weeks of training in a clinic setting or therapy session. Thus, moving external feedback to the natural setting has the potential for even greater rehearsal during daily activities. A new treatment via wearable systems offer a way to automate the detection of gait patterns and produce external feedback thus potentially meeting the need to provide motor re-learning intervention in the natural environment. In the current work, we conducted a feasibility study to understand if a wearable system we previously developed–Smart Stepper–will work in a real-life environment. We employed several of Bowen et al. (2009) suggestions of focus areas for feasibility studies based on the stage of the intervention's development. According to Bowen et al. 2009, feasibility studies can be conducted at 3 stages to answer "can it work", "does it work", and "will it work" (Bowen et al., 2009). Our previous work and related work to answer "can it work" and "does it work" from a technical feasibility perspective is discussed in detail below. The aim of the current work is to understand the third question, "will it work" from a human-factors perspective.

1.1. Can it work

Feasibility studies aimed to determine "can it work" explore the potential for an intervention to work by asking if there is any evidence that it might (Bowen et al., 2009). To design a wearable system for extended home use, several factors were considered for it to be feasible. The first hurdle was technical–to automate and accurately detect gait events. Recent researchers have utilized Inertial Measurement Unit (IMU) sensors to capture common gait parameters in clinical settings of healthy adults (Soangra et al., 2011) as well as those with Parkinson's Disease (Anderson et al., 2018). More recently, researchers have demonstrated automated gait detection (Pollind et al., 2019)among children with idiopathic toe walking using IMU. This later approach specifically targeted real-time vibrotactile feedback during the foot strike event, as opposed to the auditory or visual feedback used in earlier studies. Therefore, it is feasible for technology to detect gait events as well as provide vibrotactile feedback.

1.2. Does it work

The second question addresses the design of the feedback system. "Does it work" in Bowen et al's paradigm refers to evidence that an intervention "efficacious under idea or actual conditions, compared to whatever other practices might be done instead" (Bowen et al., 2009). Previous work found the use of textured in-soles led to lowered gait speeds, step length, and stride length in the elderly but had no effect on balance (Hatton et al., 2012). In contrast, the vibrotactile feedback with subsensory vibratory actuators insoles was effective in reducing stride, stance, and swing time variability in gait in the elderly which was hypothesized to reduce fall risk (Galica et al., 2009). The Smart Stepper system provided feedback if subsequent toe strikes were detected and continued until the child reverted to heel strike gait. Simultaneously, a smartphone records the number of heel vs. toe contact during foot initial contact, which provide children, parents, and clinicians daily feedback on gait performance (Pollind et al., 2019). While early pilot studies documented success in increasing heel strike, the intervention period was limited to a few days, and they did not explore the user experience of the family in the home environment. To address this gap, we previously deployed a functional prototype developed (Pollind et al., 2019) and validated (Soangra et al., 2021) to provide automated vibrotactile input via shoe inserts linked with a smartphone application.

Motor learning has been utilized with idiopathic toe walking in four different studies to increase heel strike frequency (Clark et al., 2010; Conrad & Bleck, 1980; Marcus et al., 2010; Pelykh et al., 2014). Two of these studies provided augmented feedback through auditory (Conrad & Bleck, 1980; Marcus et al., 2010) and one through visual feedback (Pelykh et al., 2014). All three of these studies report positive changes in the gait pattern over multiple days and weeks of training, however, none of these studies report normalized gait. Conrad (Conrad & Bleck, 1980) implemented auditory feedback during a home program for one-hour of training per day, while Marcus (Marcus et al., 2010) utilized auditory feedback at school. While both authors utilized feedback systems outside of a clinic, use in the natural environment during typical school activities was only achieved by Marcus (Marcus et al., 2010).

1.3. Will it work

"Will it work '' feasibility studies examine real-life contexts, settings or populations that might adopt an intervention (Bowen et al., 2009). The aim of this current work is to understand the feasibility of the Smart Stepper system after extended use within the natural environment. We are interested in the feasibility of real-life context to determine if Smart Stepper would work. We surveyed child and parent participants post-intervention regarding feasibility factors of Acceptability, Demand, Implementation, Practicality, and Limited efficacy (Bowen et al., 2009).

2. Smart stepper system

The Smart Stepper system implements a real-time vibrotactile motor re-learning intervention by carefully combining several components: the form factor (shoe insert and phone app), the embedded sensors, the foot strike detection algorithm, and the interaction design. To automate the real-time prompting provided by parents regarding toe walking, it is critical to differentiate accurately toe-to toe versus heel-to-toe gait patterns in a child's natural environment. Once toe walking is identified, private, real-time motor re-learning feedback is provided to encourage heel strikes. To accomplish this task, several components were assembled: sensors, algorithms, form factor, and the interaction design of the vibrotactile feedback. Integrating the components was done with consideration to the robustness of the system as this wearable requires that participants don the system over the course of weeks or months.

2.1. Sensors

We utilized inertial sensors (consisting of accelerometers and gyroscopes) as data input for machine learning algorithms to classify gait patterns. Previous research provides insights on how foot contact dynamics are affected during toe walking (Soangra et al., 2021) and how sensors (Pollind et al., 2019) and machine learning algorithms (Kim et al., 2019) can detect toe walking patterns (Ershadi et al., 2021). Researchers have also established the technical feasibility of using sensors and machine learning for detecting toe walking (Kim et al., 2019; Pollind et al., 2019).

2.2. Algorithm

In the Smart Stepper system, the algorithm consists of a deep learning neural network with input layers for raw sensor data (IMUs) as input and output layers with two classification labels (toe-to-toe versus heel-to-toe strike). The model was pruned, quantized, and embedded in an Arduino Nano 33 BLE Sense using TensorFlow Micro. Pilot experiments were conducted to determine accuracy of toe walking classification before deploying the Smart Stepper system to the participants. We found an accuracy of 94.3%, with sensitivity of 89.3% and specificity of 99.3% using deep learning model such as long short-term memory (LSTM) (Kim et al., 2019).The embedded deep learning model detected the lack of a heel strike and relayed this information in real-time via Bluetooth to the smartphone. The real-time algorithm is necessary to confirm when a heel strike is absent which is a key component of motor-relearning.

2.3. Form Factor

The Smart Stepper system consists of a 3D-printed shoe insert with embedded sensors and a microcontroller in the heel that vibrates when a heel strike is absent, see Fig. 1. Given the hardware and software requirements of the Smart Stepper system, we built the shoe insert out of NinjaFlex (Leite et al., 2019) 1.75mm thick midnight black filament. NinjaFlex materials have superior flexibility and longevity compared to non-polyurethane materials (Hussain et al., 2018). The material's elongation allowed for repeated movements and impact without wear or cracking. This material was chosen because it has 20% better abrasion resistance than ABS (Acrylonitrile Butadiene Styrene) and 68% better abrasion resistance than PLA (Polylactic Acid), which is commonly used in 3-D printed insole materials.The 3D accelerometer and gyroscope sensors embedded on the Arduino Nano Sense BLE with microcontroller were chosen because they afford the ability to deploy ML algorithms to provide real time toe walking classification.

2.4. Interaction Design of Vibrotactile Feedback

Creating new forms of sensory feedback in devices requires addressing individual child participants' sensory perceptual thresholds. Previous research findings regarding wearer's perception of vibrotactile feedback have been contradictory. Researchers have found that vibration stimuli may not be recognizable feedback information or that it can become uncomfortable if used for a longer period (Alahakone & Senanayake, 2009). Children with idiopathic toe walking have been shown to be both more sensitive to vibrotactile perception (Pollind et al., 2019) as well as being less sensitive (Ganley & Behnke, 2016) than non-toe walkers. Given this variability in previous work, the vibration in the Smart Stepper at the heel was varied and delivered between 150-180 Hz which has been found to be the optimal vibration frequency range in mobile environments (Yim et al., 2007).

Another potential concern that we considered is phantom vibration syndrome which could lead to sensation of vibration when in actuality there was no vibration (Deibel, 2013). The Smart Stepper system addressed the concerns through the varied duration of the vibrotactile feedback. The duration of vibration was kept random from 100 to 500ms to ensure minimal learning and adaptability (i.e., sensory habituation (Fanchiang et al., 2016)) among the participants. Specifically, the interaction involved a prompt hierarchy starting with three, six, then nine consecutive toe-to-toe steps that elicited intermittent random vibration among participants. When 10 consecutive toe walking steps occurred, then a 30 second vibration occurred. The smart phone displayed summary feedback of 2 gait patterns: heel strike and toe walking (see Fig. 1c).

3. Methods

We conducted post intervention surveys to understand key areas of feasibility (Bowen et al., 2009). Specifically, we were interested in understanding if Smart Stepper would work in a real-life context and if families would be willing to adopt the intervention as a practice. Areas we focused on were Acceptability, Implementation, Demand, Practicality, and Limited efficacy.

3.2. Participants

In Southern California, twenty families who have sought physical therapy for their children's toe walking participated in the deployment of the Smart Stepper system within the home setting. Researchers requested the children wear the system intensively for a month. Participants wore the

Smart Stepper insert for 8-39 days and maintained bi-weekly consultation with the physical therapist (see number of days of use in Table 1). The system was available for an additional 6 months because in some instances the insert would break, requiring replacement and some children grew out of their shoes. At the completion of the deployment, participants were invited via email to complete two surveys regarding their opinions on the overall system and intervention.

Table 1
Child and Parent Demographics of Participants who responded to the survey. The * indicates the child did not complete the survey.

Child ID	Parent ID	Child's age	Days of Use	# of shoe replacements
C1	P1	9	34	3
C2	P2	9	23	0
C3	P3	13	30	1
C4	P4	8	31	4
C5	P5	9	39	1
C6	P6	9	22	2
*	P7	7	21	1
*	P8	10	8	1

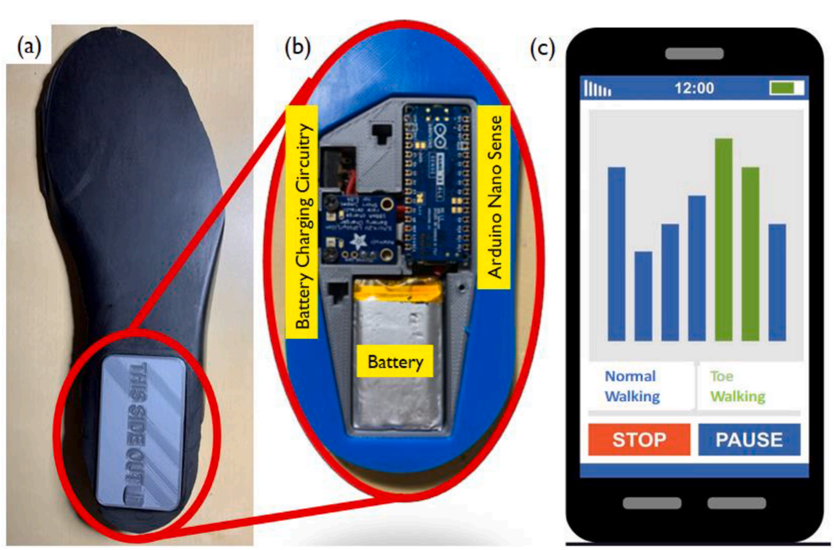

Fig. 1. (a) Smart Stepper Insole designed with circuitry at heel, (b) System on chip (SOC) along with battery and vibration motor, (c) Smartphone Interface showing real-time classification of toe walking characteristics.

3.3. Survey Study Procedure

This study was approved by our university's Institutional Review Board (IRB #20-219) and prior to the initiation of data collection, participants provided informed consent and assent. Child and parent surveys were designed using Qualtrics software. The two surveys were deployed a few weeks after the deployment study concluded. A second survey was deployed to clarify responses. Surveys were emailed to the parents of the 20 families that participated in the system deployment. Six children and eight parents responded to the user experience survey, (see Table 1). This response rate is slightly below the acceptable, pre-covid expectations of 67% (Sitzia & Wood, 1998). Families who completed both surveys were compensated with a $5 gift card. From the twenty families, a total of 14 surveys were completed. Eight surveys were from parents of children 7-13 years old and six from children ages 8-13 years at the time of survey collection. Data from the surveys were reviewed and the open ended questions were analyzed by two research assistants for common themes using the framework provided by Bowen and colleagues (Bowen et al., 2009).

4. Results

The analysis of the survey data reveals several themes and trends in feasibility. These child and parent insights are unique and have not been investigated by earlier studies. We uncovered insight regarding the user experience from both the child and parent perspective regarding the Acceptability, Demand, Implementation, Practicality, and Limited Efficacy of the Smart Stepper system in family life (Bowen et al., 2009).

4.1. Acceptability

Drawing on Bowen et al' s recommendations (Bowen et al., 2009) for focus on *Acceptability,* we asked families about their satisfaction & intent to continue use, perceived appropriateness, and fit for daily home life.

4.1.2. Satisfaction and Intent to Continue Use

The survey results indicated that the Smart Stepper system was identified as a preferred method of intervention because it was easier to implement than other alternatives. Multiple parents commented on the benefits of the shoe insert compared to casting or orthoses with one parent stating, "Shoe inserts are better as it has built in vibration that reminds my son not to toe walk," -P1. We asked how long parents would be willing to continue using the system. Additionally, three participants reported that they would continue using the system for approximately one year while five participants stated that they would continue using the system until toe walking was corrected or improved. Three children responded to a follow-up survey and indicated they would wear the Smart Stepper system for 50% to 90% of the day and from a "couple of days" to a "couple of months". (C1, C4, C6). Sixty-three percent of the parents stated they would like to continue using the system and 87% reported their child would be willing to try a new version.

4.1.3. Perceived Appropriateness and Practicality

The invisibility of the Smart Stepper system was perceived as an appropriate intervention for home use. The Smart Stepper system may be less stigmatizing than other interventions such as auditory cueing and children were willing to wear them. The families reported the perception reduced stigma. We found many parents feared the potential of other children discriminating against their child by "making fun of" their child for the way they walk. For example, P1 stated they appreciated that the insert allowed for privacy by "being less obvious as it doesn't make my son stand out like wearing leg braces". Additionally, children expressed satisfaction when they talked about their improvements and the chance to wear preferred types of shoes (i.e., "dress shoes and flip flops").

Regarding *Practicality*, we asked about the ability to carry out the intervention's positive and negative effects on participants. We found the physical comfort of the shoe comfort to be an important factor of a system's practicality. Overall, the children felt the shoe insert comfort was acceptable with a few outliers (i.e., one child stating it was uncomfortable and one child stating it was very comfortable). This is a tension to consider along with the technical feasibility of getting sensors and microcontrollers embedded in a shoe insert. Children informed us of ways to make the Smart Stepper system more comfortable such as using a thinner insert (C4, C6). C1 said "The inserts are too bulky. Maybe make the shoes wider to not make it not tight". C3 stated the inserts were hard and wanted a "higher arch". And another child added "more padding, [as] inserts were hard," and that the system would be good for "someone who is less sensitive to the vibrations so that they would actually put their heels down"-C5. This input presents the potential for tension between some parents who may believe children may not feel the vibration and children stating it can be uncomfortable to step down on the sensor, regardless of sensing the vibration. Adjusting the physical qualities of the shoe insert will be explored in future design iterations.

4.1.4. Positive Effect on Family

Improved parent-child communication was another positive outcome of using the system. Parents were asked if their interactions had changed with their children after seeing the data (app summary). Two parents said it allowed for better communication to discuss toe walking with their child. One parent stated: "I am able to explain more when he is on his toes or heel by showing the data to him" P1. These responses suggest that based on the parent interaction with the system, communication regarding toe walking was improved. And a few parents said they were able to use the data to implement a reward system as captured in P3's comment that "he did get praised when the count showed more heel strikes than toe steps". P6 said "We would cheer, and he'd get a special treat after dinner when he did a certain amount of heel strikes". Thirty-eight percent of parents reported that their parent-child interaction had improved after initiation of the system. When asked for further detail in this regard, one parent responded by stating "No... but since the study, my child has taken a more positive stance on being told to 'get off your toes' or 'down' or 'flat' or 'heels'."- P3. Another parent responded, "Yes, being able to recognize toe walking"-P7. From this statement, it is understood that this parent is now better able to recognize when their child is toe walking, which suggests that this system may be appropriate for helping parents to identify toe walking in their child. All the parents stated that they shared their interpretation of the (app summary) data with their child.

4.2. Demand

Demand as a feasibility factor according to Bowen et al. (2009), consists of "Post-only design with multiple surveys over time to test reactions to the intervention of a new population". We asked about perceived demand as well as the parent participant's report of actual use.

4.2.1. Perceived Demand

We sought a clear understanding of the demand for wearable intervention. Parents were motivated to increase the children's awareness of toe walking and to reduce their child's pain. One parent stated this concern most clearly when they said "Toe walking is causing a lot of problems for my child. Her toes are cramping, her skin on her toes are splitting and she trips and falls"-P5. Other parents expressed similar sentiments as P6 stated,"My son complains that his calves hurt and I know it's from the toe walking so I want to find a way for him to be in less pain". The reduction in pain was the central theme for children as well. All the children surveyed said that they would like to change their toe walking. When further questioned as to why, some children indicated to reduce pain. One child said, "So that my legs don't feel stiff when I walk sometimes''-C6. Another child reported, "To reduce trips and falls, pain, and deformed toes. Be able to wear flip flops and dress shoes."-C4.

Parents are also aware that their children may not connect their pain with toe walking. One parent reported her child was not tracking their toe walking by stating "he isn't aware of his walking gait at the conscious level," P4. One parent was sure of the connection themselves as P7 stated "My son complains that his calf's hurt and I know it's from the toe walking so I want to find a way for him to be in less pain." Some wanted to help their child be free of the pain from toe walking as well as help others. This wish was exemplified by one parent who said, "We want a pain free, normal life for our toe walking child. And if the data from these trials can be used to better diagnose and treat toe walking children earlier in life; that would be outstanding,"-P3. One parent went so far as to suggest that the system should be designed for "early toe walkers to prevent kids from developing idiopathic toe walking"-P4. In summary, the children and parents demonstrated a demand to reduce pain and connect the child's awareness of toe walking to that pain.

4.2.2. *Actual Use*

The core function of the system was to provide vibrotactile feedback that the child could perceive and comfortably act upon. The survey results confirmed that the vibration provided by the system was perceived, however exhibited low awareness and habituation. We found that the functional prototype provided enough vibration to elicit a report that 83% of the children did feel the vibration when they took steps. This is encouraging, however there is room to improve as only 57% of the children reported they "often" felt the vibration even when they were taking steps on their toes–with only one child stating they "always" felt the vibration at all time periods.

These findings indicate that the vibration may need to be stronger for some children. In fact, 66% of the children reported that the amount of feedback given was "not enough" stating that they would prefer a stronger (C6) or longer vibration (C3). Despite the limited perception of the vibration, 66% of the children still reported that they paid attention "often", and 100% said they paid attention to the feedback at least "sometimes". Additionally, in response to the vibration, 50% of the children reported making efforts to walk on their heels. For example, C4 stated that "walking changed immediately after putting on shoe inserts", and C5 stated their response to the vibration was to "walk flat foot and stomp if it still kept vibrating". A parent stated "When he was focused, he would pay attention to the shoes more and would mention when it was vibrating so I know he can feel it but if it was stronger, he'd probably stay off his toes more''-P7. We are encouraged that the parents and children are reporting similar patterns and found repeatedly that parent interpretation of the child's response to the shoe vibrating, and the child's perception of the vibration were in sync across the 3 time periods of the study, see Fig.s 2 & 3. Our findings suggest that when the children most consistently felt the vibration, they also performed the greatest consistency of heel strikes according to the parent report.

Of interest is the varying rates of vibrotactile perception over three periods of time: before initial use, after a few days of use, and during the final days of use, see Fig. 2. As the child's perception of the vibration declined, their responses also became more inconsistent. We have considered a few possibilities for this decreasing trend. It could be viewed as habituation; an overall decrease in toe walking; or false positives by the system itself. We feel the latter is not likely as there was unanimous agreement from the parents that the summary did reflect the effort and performance of their child to some extent. Parents also comment on the positive impact of the feedback as P5 said "It helps my child visually see proper walking and she strives for more green. Seeing improvement helps to continue to work towards our goals".

4.3. *Implementation*

Regarding *Implementation*, we asked about the degree of execution, success and failures with execution, factors affecting implementation ease or difficulty.

4.3.1. *Ease of Use*

We surveyed parents and children regarding the system's ease of use. Parents found the system easy to use for several reasons. Survey results showed the Smart Stepper was easy to use because of the support and assistance provided by researchers, the compatibility of the system, and the automatic and consistent reminders that heels needed to be on the ground. Parents' concerns with the shoes were described as needing to be more durable and have better connectivity with the system. It was also obtained that parents desired a system to confirm the Smart Steppers overall accuracy. The natural setting for use seemed acceptable as three parents identified school and other activities as being the perfect environment to use the shoes, as there was an "ease of using especially when going out or going to school vs. leg braces"- P1. Another parent said that they were motivated to use the system because of "the ease of just putting the inserts in the shoes"-P1. P7 said:

"The inserts were easy to put on. We had some problems with connecting phones. Inserts would have problems during use and not recording information. The inserts caused her heel to be raised up to high...The system was made easier to use by assistance provided by [senior researcher] and personnel who worked in the lab".

4.3.2. *Connectivity*

Although the shoe insert component worked overall, the connectivity was a concern at times. A few parents felt the system was easy to charge and connect, and stated "You just charge it, turn it on and connect to the app and you're good to go," P1, and P2 stated "The app and the shoes were easy to sync, and we had no trouble getting used to the system". Some issues resulted in difficulty with syncing as P2 stated "When we would leave the house and the WIFI would get disrupted, not counting all of our steps". Parents also reported challenges with the system disconnecting or not recognizing which insert was being used that day. P6 said:

"Sometimes the shoes wouldn't stay connected, or I would unplug them from the charging cords, but they wouldn't have any charge. Also, it was hard to make sure they were charging correctly the first few times. [The shoes worked well] when they connected with no issues and tracked all day long".

Others also had difficulty with connectivity. For example, P8 said "we had quite a few technical problems and became very discouraged.

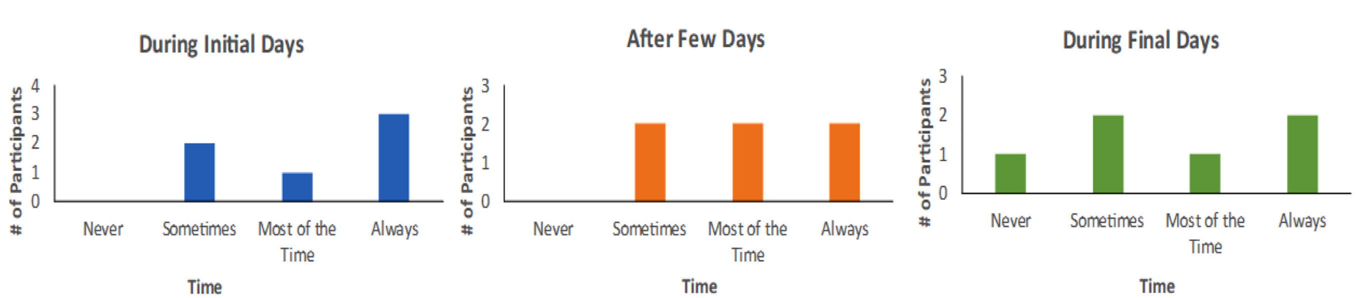

Fig. 2. Graphs depicting the child's perception of the vibration felt during three time intervals. Left: initial use; Middle: a few days of Use, Right: final days of use.

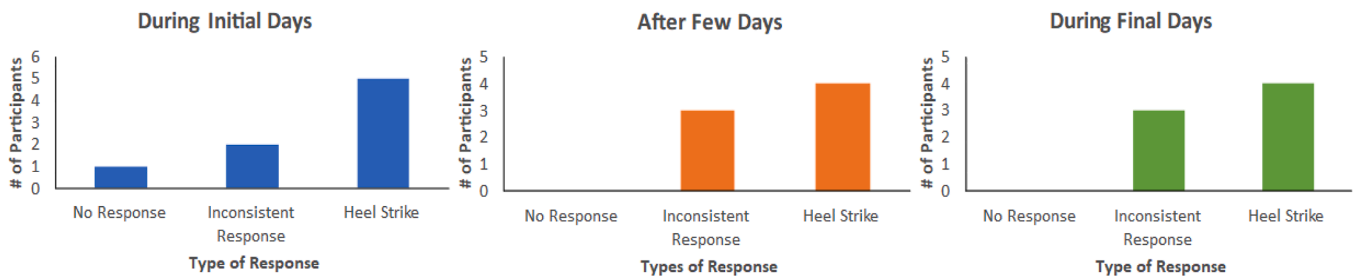

Fig. 3. Graphs depict the parent report of the child's response to vibration during three time intervals. Left: initial Use, Middle: a few days of use, Right: final days of use.

Once the glitches are worked out, it would be a fairly easy system to use". P7 said: "The system had difficulty getting connected and starting up. Process would take several attempts. She would go to school, and it would disconnect. The app did not always recognize which insert was being used that day".

4.3.3. Accuracy

Some parents and children were concerned with the system's accuracy. The system was validated for accuracy as described earlier, however some child participant's interpretation of the vibrotactile and the visual feedback resulted in confusion when it did not match their perceptions. The system was carefully calibrated yet the awareness of what constitutes a heel strike is still emerging for some participants. Half of the children reported being confused about the system's ability to detect improvements in their gait and only two children felt supported or that the system gave clear feedback. For example, C5 stated "make it vibrate only when walking on toes not when flat foot". This concern trickled down to the parents who also expressed concerns with accuracy such as P8 said "He improved when the inserts were working". Additionally, one parent requested a specific form of the data analysis, when they said, "some data analysis would have been useful for parents (histogram, etc.),"-P4.

4.3.4. Durability

Duration of the post interventions survey and durability were the main concerns regarding the execution of the system deployment. C6 said "I think I needed more time to really get used to the inserts and how everything works because of the pandemic. I haven't been leaving my house as much as I did when I first got the shoes." Another parent expressed the impact of the COVID-19 pandemic on being able to use the system as P8 said: "It would have been fine [with] my son in a more normal time and if the inserts were able to handle more. I think it is a good system for kids or adults. [However], the system was proving to be more stressful than useful- especially during the pandemic when we're stuck in our house. We likely would have stuck with it longer (indefinitely) if it had worked more smoothly".

Durability was the biggest challenge of the Smart Stepper system. As a prototype, it was more fragile than parent participants would have preferred. For example, P3 stated: "The usability of the app and insole was easy enough to learn and maintain functionality. The weak part of the system was having the electronics housed in the heel of the insole. When my child did walk on his heels, it led to the breaking of the insole electronics. We only got 3-4 days of light walking and wearing before they would stop working. The perfect environment for us was inside large retail box stores, or malls. If my child wore the shoes to school, they broke the first day; probably at recess or lunch play. If the system could be worked in such a way as to make the system more durable to the rigors of daily wear..... these insoles would be priceless!" Durability is a consideration that is difficult to address in an early prototype deployment, yet it is important for an understanding of a system's use in a natural setting.

4.4. Limited Efficacy

Regarding *Limited efficacy*, we asked about the intended effects of the smart stepper on toe walking.

4.4.1. Intended Effects

The survey results suggest that the system was effective in addressing idiopathic toe walking over time and even after cessation of intervention. Improvements were seen in the amount of toe walking compared across time. The longer the shoe insert was worn, the greater gait changes were observed by both parent and child suggesting that a longer intervention would be more effective. Similar trends in perceived gait changes were reported by children and parents, see Fig. 4 Left. Although there are slight differences between the parent and child perception of toe walking, the overall trend is the same (See Fig. 4 Left). These results demonstrate the perceived efficacy of this Smart Stepper intervention. This is supported by parent reports of perceived efficacy with 50% saying it was "very effective" compared to their previous interventions, see Fig. 4 Right. Insights related to the trends over time were also discussed.

At initial use of the shoes one parent reported "whenever he is not wearing the shoes, he is up on his toes" -P2; another parent reported "My child was able to walk flat footed for long periods of time when wearing the inserts" -P5. While another stated "just wearing those shoes put him in a mode to walk on his heels"–P3. Even in the initial days of the intervention, "toe walking was less" -P1 and parents reported "improved gait but needed some parental reminders" -P8. P7 stated "Once we started (the) toe study that is when we started noticing a big improvement". After multiple days of wear children were able to tolerate wearing the shoe as evidenced by P7 report that "the inserts were worn the length of study until covid. At that time, we wore them until shoes no longer fit". After multiple days of wear, 88% of parents and 50% of children were able to detect a change in their gait which suggests a time dependent component to this intervention.

Following multiple days of wear, comments on awareness were prevalent. P3 reported "while the insoles worked, we saw him constantly aware of his heel to toe strike ratio". Parents also reported less reminders on their part as P8 stated "Let's [less] reminders to stay off his toes" and P1 stated "the toe walking has lessened a bit". Children were also aware of these improvements as C6 stated they "walked more flat footed". P7 observed that during periods when shoe inserts were not worn for multiple days, "She would start walking more on toes rather than doing toe heel strikes''. P8 demonstrated some habituation to the system and stated, "he eventually started ignoring, or taking longer to notice the prompt, but still responded".

Immediately after deployment of the system, it was observed that there was a slight increase in the amount of toe walking from the end of the intervention to the time of survey completion. However, the parent and child still reported a 12% and 7% decrease in toe walking respectively compared to before the intervention. Both the parent and child perceived the greatest decrease in toe walking immediately post intervention, with 15% and 16% decreases respectively. Multiple days after

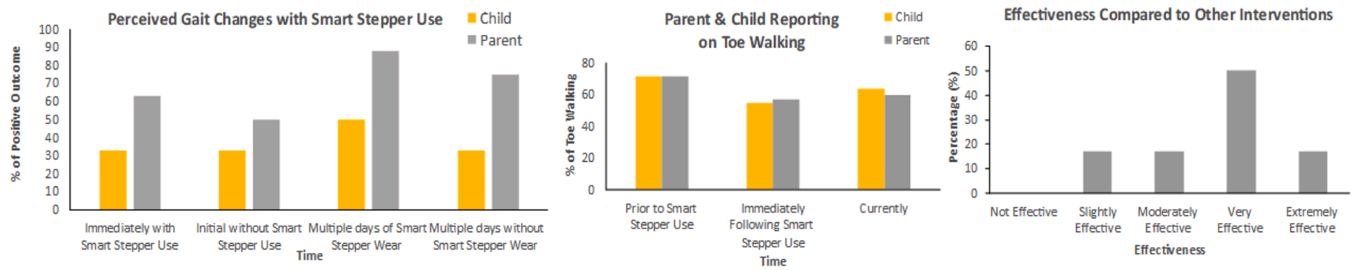

Fig. 4. Left: Graph of child and parent perceptions of gait changes during four time intervals. Middle: Graph comparing the percentage of perceived Toe Walking at three time intervals, Right: Graph depicts parental report of efficacy of the intervention compared to other interventions previously tried.

the last use, 75% of the parents were still able to detect a change in their child's gait. This provides initial evidence that there may be long-term benefits in correcting gait mechanics after the cessation of shoe use. Following multiple days without wear, the children were observed to regress to a certain extent with parents stating "he went back to[e] walking"-P1. Taken with the data suggesting greater gait changes with multiple days of wear, this suggests that additional benefits would continue to be observed with a longer period of intervention.

4.4.2. Maintenance of Changes from Initial Use

In surveying the children and parents about what changed over the time using the system, we found the system brought some awareness to their toe walking. P7 stated the system "made her aware of how her legs felt if she was having pain from toe walking" and added the system would be useful for "any child who was unaware of toe walking and needed it to be identified". Regarding the child's awareness of their toe walking, we found that toe walking is difficult for children to perceive and thus resulted in parents verbally prompting their children. Specifically in our survey, when the children were asked what makes them walk on their toes more, they either did not know or stated when they did not have any external cues, such as when they were "walking barefoot"-C2. These findings support the use of an external cue as necessary to indicate to children who toe walk that they are on their toes. This concept is supported by a response from a child themselves who realized the effect of the external cue in the shoe stating, "I should wear shoes more now that I am typing about it"-C2.

Improvement in heel strikes motivated continued use of the system. C4 said they felt "hopeful because it was working". P8 said, "Improvement would motivate. I liked seeing improvement. It was positive in that we could discuss what helped. He definitely is motivated by it". P6 said, "He was excited about his progress when he wore the shoes". Another parent summarized the sentiment for their intent to continue with using the Smart Stepper system. P7 said "I would be willing to use the system as long as it was showing improvement. The reason we agreed to participate was to improve walking without being on toes".

5. Discussion

In exploring the rich user experiences of the families that used the Smart Stepper system, we have demonstrated that the system is feasible in a real context by examining Acceptability, Demand, Implementation, Practicality, and Limited Efficacy. This study provided design insight regarding the child and parent experiences in a natural setting over time. These user experiences from children and their parents regarding vibrotactile perception are novel contributions to the wearable literature. The insight that children are not always aware of their own toe walking and its impact on their pain can be considered when parents, clinicians, designers interpret the child participant's feedback. Prior to this work, little was known about the child's perspective regarding toe walking and the associated interventions. For example, one such study found a negative impact on quality of life as idiopathic toe walking children scored lower than healthy controls on Total, Psychosocial, and Emotional subscales of the PedsQL 4.0, thus demonstrating the overarching effect toe walking can have on their life (Williams & Haines, 2015). The need to understand the experience of toe walking and the experience of wearable interventions has led to this work which revealed places of balance and place of tension.

5.1. In Balance

Family members were in balance regarding satisfaction with the system. When parents and children were in alignment with their *satisfaction* with the system, shifts in family communication around toe walking and interventions were possible. Satisfaction was driven by the child and parent seeing improvement in gait and decreased pain. The intended effect to support awareness of what is causing pain plays a role in the *limited efficacy* of this study. The child and the parents' desire to see change is a highly desirable type of motivation for a therapeutic system as "mastery motivation" is the kind that leads to the adoption of a wearable system. Overall, showing the daily data increased awareness of toe walking as well as increased the child's motivation, allowing the child to be more receptive to parental cues.

Regarding the practicality of the system, the ease of use and invisibility of the feedback which could reduce stigma, as well as provide an ideal condition for motor re-learning through the immediacy and automaticity of feedback. Parents are highly concerned with the impact of their child's toe walking not only because of the physical pain it causes but also the potential stigma. Stigma should be considered when designing assistive devices (Shinohara & Jacob O. Wobbrock, 2011) or wearable devices to ensure social acceptability (Boyd et al., 2017; Shinohara et al., 2018). therefore an ease to use and practical system is of value.

5.2. In Tension

Tensions in execution were noted regarding the execution of the system in a home setting. Insights regarding the pain points of using a wearable in the natural setting include the practicality regarding durability and comfort of the system. It is highly encouraging that parents reported that they want to continue using the system until toe walking is corrected if the system is updated and there was an increase in durability of the shoe inserts. Ongoing use will require customizing for vibrotactile comfort of the insert and the feedback. Given idiopathic toe walking children may be predisposed to sensory processing difficulties such as hypersensitivity (Williams et al., 2012) customizing for comfort is key. The frequency of vibration can be varied with different inter-vibration timings and the design of future shoe inserts could focus on hardness on the heel. Despite our efforts to use flexible and durable materials, for some, that hardness of the shoe insert had the unintended effect of making it less likely for the child to walk on their heels.

The vibration provided by the system worked and the children would have preferred a strong/longer vibration. The children experienced a decrease in vibration over time that could be due to adaptation. Further study is required however we found that the longer the shoe insert was worn, the greater gait changes were observed by both parent and child. This suggests that a longer intervention could be more effective. Additionally, the varied perception of vibrotactile input in some cases reveals the need for developers to maintain a role in improving the user experience through calibration settings for child and parent participants. A ground truth metric would have allowed parents and children to check that the system was working and adjust their perception of what constitutes a heel strike. This is a valuable lesson that is at the core of motor re-learning. Design work on how to make this feasible could be addressed in future iterations.

Improvements to the shoe need to focus on comfort for the child including durability for rugged use, customizable vibrotactile input and flexibility of the insert. Finding a balance between having the sensors placed in a feasible location while not being too soft of a material that the sensor would be felt by heel strikes. With improvements to durability and comfort (e.g., and thinner, softer, higher arch insert), the shoes can be used in any environment. However, overall, the invisible shoe insert paired with a mobile phone as a form factor is easy to use and less stigmatizing than other interventions and children are willing and motivated to wear them.

The feedback on the phone promoted a starting place for parent-child communication related to awareness and pain associated with toe walking. With the need to balance data sharing amongst family members with the child's privacy, we began with discrete feedback in real time through vibrotactile input for the child as well as shareable summary on a smartphone for the family. However, as this system is a functional prototype to test for feasibility in a natural setting, it did not have the capacity to save the gait data beyond the current day/week, yet the utility of this configuration has been demonstrated. What was learned from this deployment was the need for a ground truth in the natural setting that all members could rely on to confirm heel strikes. Although the development and testing of the efficacy of this system had been previously established (Soangra et al., 2021); children and parent participants doubted the system at times, derailing the core function of the system. The system's physical robustness including the system's connectivity had a positive impact on the family members connecting to each other regarding the presence of heel strikes.

6. Conclusion

The Smart Stepper system was reported to promote heel strikes as well as reduce pain, fall risk, and potential stigma. Additionally, several insights contribute to the understanding of families who use wearables in natural settings over time. Previous studies on wearables have not addressed the need for real time feedback to promote motor re-learning in natural environments for extended periods of time nor have they explored the user experience of children and their parents regarding home use. We addressed this gap by deploying a functional prototype previously developed (Pollind et al., 2019) and validated (Soangra et al., 2021) to provide automated vibrotactile input via shoe inserts linked with a smartphone application. In this work, we surveyed children and parents regarding the child and parent participants' experience with the Smart Stepper system after their extended use of the system at home. The survey results indicated the Smart Stepper system supports perception of improved gait patterns by children and parents, the system was easy to use, motivated ongoing use, alleviated pain, and supported positive parent-child communication regarding toe walking. The system was reported to be effective in addressing idiopathic toe walking over time, even after cessation of intervention. These design insights will be incorporated in the next iteration of the Smart Stepper system. These design implications may have utility for other therapeutic wearables that involve similar stakeholder groups made up of children, parents, and clinicians.

6.1. Implications

Designers of therapeutic wearable systems for children should consider ways to reduce frustration by adding the ability to confirm ground truth as a method to demonstrate the system is consistently accurate and reliable. Other implications for future design are to: change the insert to improve durability for robust use in daily life; add more user training; optimize connectivity; customize user interfaces for multiple types of users; customize vibrotactile feedback as well as customizing the insert's shape and feel for comfort.

Future work could explore ways to customize the physical aspects of the insert with new technologies for 3D printing such as Fused Deposition Modeling 3D printers that allows for each voxel to be customized in terms of flexibility and strength, thus providing a highly individualized fit, thus improving the user experience across several pain points for the family of wearables in a natural setting.

6.2. Impact Statement

This research paper takes an important first-time look at family experiences (children and parents) regarding a device for rehabilitation. While this is a first look at how children feel about wearables for physical therapy, the impact of the work has a sustainable broader impact on the design of wearable interventions. The intellectual merit of the project is the novel application of Machine Learning to classify gait. This paper provides an important step to ensure wearable devices are usable by children and parents. This work explores these vital human factor parameters in feasibility.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rahul Soangra has patent Device for treating idiopathic toe walking pending to 17181238. NIL

Acknowledgements

We thank the families who participated in this study. We thank research assistants and collaborators.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Alahakone, A. U., & Senanayake, S. M. N. A. (2009). Vibrotactile feedback systems: Current trends in rehabilitation, sports and information display. In *2009 IEEE/ASME International Conference on Advanced Intelligent Mechatronics* (pp. 1148–1153). https://doi.org/10.1109/AIM.2009.5229741

Anderson, B., Zhu, S., Yang, K., Wang, J., Anderson, H., Tay, C. X., Tan, V. Y. F., & Wang, Y. (2018). MANA: Designing and Validating a User-Centered Mobility Analysis System. In *Proceedings of the 20th International ACM SIGACCESS Conference on Computers and Accessibility* (pp. 321–332). https://doi.org/10.1145/3234695.3236340

Babb, A., & Carlson, W. O. (2008). Idiopathic toe-walking. *South Dakota Medicine, 61*(2), 55–57, 53.

Bowen, D. J., Kreuter, M., Spring, B., Cofta-Woerpel, L., Linnan, L., Weiner, D., Bakken, S., Kaplan, C. P., Squiers, L., Fabrizio, C., & Fernandez, M. (2009). How We Design Feasibility Studies. *American Journal of Preventive Medicine, 36*(5), 452–457. https://doi.org/10.1016/j.amepre.2009.02.002

Boyd, L. E., Jiang, X., & Hayes, G. R. (2017). ProCom: Designing and Evaluating a Mobile and Wearable System to Support Proximity Awareness for People with Autism. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems* (pp. 2865–2877). https://doi.org/10.1145/3025453.3026014

Caserta, A., Reedman, S., Morgan, P., & Williams, C. M. (2022). Physical activity and quality of life in children with idiopathic toe walking: A cross sectional study. *BMC Pediatrics, 22*(1), 544. https://doi.org/10.1186/s12887-022-03583-w

Clark, Sweeney, Jane, K, Yocum, Allsion, & McCoy, Sarah W (2010). Effects of Motor Control Intervention for Children With Idio... : Pediatric Physical Therapy. *Pediatric Physical Therapy, 22*(4), Article 4170426.

Conrad, L., & Bleck, E. E. (1980). Augmented Auditory Feedback in the Treatment of Equinus Gait in Children. *Developmental Medicine & Child Neurology, 22*(6), 713–718. https://doi.org/10.1111/j.1469-8749.1980.tb03737.x

De Oliveira, V., Arrebola, L., De Oliveira, P., & Yi, L. (2021). Investigation of Muscle Strength, Motor Coordination and Balance in Children with Idiopathic Toe Walking: A Case-control Study. *Developmental Neurorehabilitation, 24*(8), 540–546. https://doi.org/10.1080/17518423.2021.1899326

Deibel, K. (2013). A convenient heuristic model for understanding assistive technology adoption. In *Proceedings of the 15th International ACM SIGACCESS Conference on Computers and Accessibility* (pp. 1–2).

Pistilli, E, Rice, T., Pergami, P., & Mandich, M. B. (2014). Non-invasive serial casting to treat idiopathic toe walking in an 18-month old child—IOS Press. *NeuroRehabilitation, 34*(2), 215–220.

Ershadi, G., Gwak, M., Aminian, A., Soangra, R., Grant-Beuttler, M., & Sarrafzadeh, M. (2021). Smart Insole: Remote Gait Detection Algorithm Using Pressure Sensors For Toe Walking Rehabilitation. In *2021 IEEE 7th World Forum on Internet of Things (WF-IoT)* (pp. 332–337). https://doi.org/10.1109/WF-IoT51360.2021.9595676

Fanchiang, H. D., Geil, M. D., Wu, J., Ajisafe, T., & Chen, Y. (2016). The Effects of Walking Surface on the Gait Pattern of Children With Idiopathic Toe Walking. *Journal of Child Neurology, 31*(7), 858–863. https://doi.org/10.1177/0883073815624760

Fox, A., Deakin, S., Pettirgrew, G., & Paton, R. (2006). Serial casting in the treatment of idiopathic toe-walkers and review of the literature. *Acta Orthopaedica Belgica, 72*(6), 722–730.

Galica, A. M., Kang, H. G., Priplata, A. A., D'Andrea, S. E., Starobinets, O. V., Sorond, F. A., Cupples, L. A., & Lipsitz, L. A (2009). Subsensory vibrations to the feet reduce gait variability in elderly fallers. *Gait & Posture, 30*(3), 383–387. https://doi.org/10.1016/j.gaitpost.2009.07.005

Ganley, K. J., & Behnke, C. (2016). Distal Vibration Perception Threshold in Children Who Toe Walk. *Pediatric Physical Therapy, 28*(2), 187–191. https://doi.org/10.1097/PEP.0000000000000241

Hatton, A. L., Dixon, J., Rome, K., Newton, J. L., & Martin, D. J. (2012). Altering gait by way of stimulation of the plantar surface of the foot: The immediate effect of wearing textured insoles in older fallers. *Journal of Foot and Ankle Research, 5*(1), 11. https://doi.org/10.1186/1757-1146-5-11

Hussain, I., Iqbal, Z., Malvezzi, M., Seneviratne, L., Gan, D., & Prattichizzo, D. (2018). Modeling and Prototyping of a Soft Prosthetic Hand Exploiting Joint Compliance and Modularity. In *2018 IEEE International Conference on Robotics and Biomimetics (ROBIO)* (pp. 65–70). https://doi.org/10.1109/ROBIO.2018.8665231

Kim, S., Soangra, R., Grant-Beuttler, M., & Aminian, A. (2019). WEARABLE SENSOR-BASED GAIT CLASSIFICATION IN IDIOPATHIC TOE WALKING ADOLESCENTS. *Biomedical Sciences Instrumentation, 55*(2), 178–185.

Leite, M., Soares, B., Lopes, V., Santos, S., & Silva, M. T. (2019). Design for personalized medicine in orthotics and prosthetics. *Procedia CIRP*, 84, 457–461. 10.1016/j.procir.2019.04.254.

Marcus, A., Sinnott, B., Bradley, S., & Grey, I. (2010). Treatment of idiopathic toe-walking in children with autism using GaitSpot Auditory Speakers and simplified habit reversal. *Research in Autism Spectrum Disorders, 4*(2), 260–267. https://doi.org/10.1016/j.rasd.2009.09.012

Oetgen, M. E., & Peden, S. (2012). Idiopathic Toe Walking. *JAAOS - Journal of the American Academy of Orthopaedic Surgeons, 20*(5), 292–300. https://doi.org/10.5435/JAAOS-20-05-292

Pelykh, O., Klein, A. M., Feist-Pagenstert, I., Schlick, C., & Ilmberger, J. (2014). Treatment outcome of visual feedback training in an adult patient with habitual toe walking. *European Journal of Physical and Rehabilitation Medicine*.

Pollind, M., Soangra, R., Grant-Beuttler, M., & Aminian, A. (2019). CUSTOMIZED WEARABLE SENSOR-BASED INSOLES FOR GAIT RE-TRAINING IN IDIOPATHIC TOE WALKERS. *Biomedical Sciences Instrumentation, 55*(2), 192–198.

Pomarino, D., Ramírez-Llamas, J., Martin, S., & Pomarino, A. (2016). The 3-Step Pyramid Insole Treatment Concept for Idiopathic Toe Walking. *Foot & Ankle Specialist, 9*(6), 543–549. https://doi.org/10.1177/1938640016669794

Rossi, E. M., Nevalainen, P., Mäenpää, H., & Lauronen, L. (2018). Soleus H-Reflex and Its Modulation With Vibration in Idiopathic Toe Walkers and Typically Developing Children. *Journal of Child Neurology, 33*(5), 351–358. https://doi.org/10.1177/0883073818759104

Sanger, T. (2004). Failure of Motor Learning for Large Initial Errors. *Neural Computation, 16*, 1873–1886. https://doi.org/10.1162/0899766041336431

Shinohara, K., Bennett, C. L., Pratt, W., & Wobbrock, J. O. (2018). Tenets for Social Accessibility: Towards Humanizing Disabled People in Design. *ACM Transactions on Accessible Computing, 11*(1), 1–31. https://doi.org/10.1145/3178855

Shinohara, K., & Wobbrock, Jacob O. (2011). In the shadow of misperception: Assistive technology use and social interactions. In *Proceedings of the 2011 Annual Conference on Human Factors in Computing Systems - CHI '11, 705*. https://doi.org/10.1145/1978942.1979044

Shulman, L. H., Sala, D. A., Chu, M. L. Y., McCaul, P. R., & Sandler, B. J. (1997). Developmental implications of idiopathic toe walking. *The Journal of Pediatrics, 130*(4), 541–546. https://doi.org/10.1016/S0022-3476(97)70236-1

Sitzia, J., & Wood, N. (1998). Response rate in patient satisfaction research: An analysis of 210 published studies. *International Journal for Quality in Health Care, 10*(4), 311–317. https://doi.org/10.1093/intqhc/10.4.311

Soangra, R., Lockhart, T. E., & Van de Berge, N. (2011). An approach for identifying gait events using wavelet denoising technique and single wireless IMU. *Proceedings of the Human Factors and Ergonomics Society Annual Meeting, 55*(1), 1990–1994. https://doi.org/10.1177/1071181311551415

Soangra, R., Shiraishi, M., Beuttler, R., Gwerder, M., Boyd, L., Muthukumar, V., Trabia, M., Aminian, A., & Grant-Beuttler, M. (2021). Foot contact dynamics and fall risk among children diagnosed with idiopathic toe walking. *Applied Sciences, 11*(6), 2862.

Sobel, E., Caselli, M. A., & Velez, Z. (1997). Effect of persistent toe walking on ankle equinus. Analysis of 60 idiopathic toe walkers. *Journal of the American Podiatric Medical Association, 87*(1), 17–22. https://doi.org/10.7547/87507315-87-1-17

Stricker, S. J., & Angulo, J. C. (1998). Idiopathic Toe Walking: A Comparison of Treatment Methods. *Journal of Pediatric Orthopaedics, 18*(3), 289–293.

van Bemmel, A. F., van de Graaf, V. A., van den Bekerom, M. P. J., & Vergroesen, D. A. (2014). Outcome after conservative and operative treatment of children with idiopathic toe walking: A systematic review of literature. *MUSCULOSKELETAL SURGERY, 98*(2), 87–93. https://doi.org/10.1007/s12306-013-0309-5

van Kuijk, A. A. A., Kosters, R., Vugts, M., & Geurts, A. C. H. (2014). Treatment for idiopathic toe walking: A systematic review of the literature. *Journal of Rehabilitation Medicine, 46*(10), 945–957. https://doi.org/10.2340/16501977-1881

Westberry, D. E., Carpenter, A. M., Brandt, A., Barre, A., Hilton, S. B., Saraswat, P., & Davids, J. R. (2021). Surgical Outcomes for Severe Idiopathic Toe Walkers. *Journal of Pediatric Orthopaedics, 41*(2), e116–e124. https://doi.org/10.1097/BPO.0000000000001677

Williams, C. M., Michalitsis, J., Murphy, A. T., Rawicki, B., & Haines, T. P (2016). Whole-Body Vibration Results in Short-Term Improvement in the Gait of Children With Idiopathic Toe Walking—Cylie M. Williams, Joanne Michalitsis, Anna T. Murphy, Barry Rawicki, Terry P. Haines, 2016. *Journal of Child Neurology, 31*(9), 1143–1149.

Williams, C. M., Tinley, P., Curtin, M., & Nielsen, S. (2012). Vibration Perception Thresholds in Children With Idiopathic Toe Walking Gait. *Journal of Child Neurology, 27*(8), 1017–1021. https://doi.org/10.1177/0883073811432748

Williams, C. M., Tinley, P., Curtin, M., Wakefield, S., & Neilsen, S. (2014). Is Idiopathic Toe Walking Really Idiopathic? The Motor Skills and Sensory Processing Abilities Associated With Idiopathic Toe Walking Gait—Cylie M. Williams, Paul Tinley, Michael Curtin, Suzanne Wakefield, Sharon Nielsen, 2014. *Journal of Child Neurology, 29*(1), 71–78.

Williams, & Haines. (2015). Idiopathic toe walking may impact on quality of life. *Journal of Foot and Ankle Research, 8*(2), O40. https://doi.org/10.1186/1757-1146-8-S2-O40

Williams, Tinley, & Curtin. (2010). Idiopathic toe walking and sensory processing dysfunction. *Journal of Foot and Ankle Research, 3*(1), 16. https://doi.org/10.1186/1757-1146-3-16

Yim, J., Myung, R., & Lee, B. (2007). The Mobile Phone's Optimal Vibration Frequency in Mobile Environments. In N. Aykin (Ed.). In *Usability and Internationalization. HCI and Culture, 4559* pp. 646–652). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-540-73287-7_75.