The Effects of Walking Surface and Vibration on the Gait Pattern and Vibration Perception Threshold of Typically Developing Children and Children with Idiopathic Toe Walking

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ACCEPTANCE

This dissertation, THE EFFECTS OF WALKING SURFACE AND VIBRATION ON THE GAIT PATTERN AND VIBRATION PERCEPTION THRESHOLD OF TYPICALLY DEVELOPING CHILDREN AND CHILDREN WITH IDIOPATHIC TOE WALKING, by HSINCHEN D. FANCHIANG, was prepared under the direction of the candidate's Dissertation Advisory Committee. It is accepted by the committee members in partial fulfillment of the requirements for the degree Doctor of Philosophy in the College of Education, Georgia State University.

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ABSTRACT

THE EFFECTS OF WALKING SURFACE AND VIBRATION ON THE GAIT PATTERN AND VIBRATION PERCEPTION THRESHOLD OF TYPICALLY DEVELOPING CHILDREN AND CHILDREN WITH IDIOPATHIC TOE WALKING

by
Hsinchen D. Fanchiang

The aim of the current study is to investigate novel therapeutic/treatment methods and outcome measurement for children with Idiopathic Toe Walking (ITW). Fifteen typically developing (TD) children and 15 children with ITW, aged between 4 to 10 years old, participated. The participants performed a gait exam including 30 barefoot walking trials over three 4-meter walkways before and after a whole-body vibration intervention. Vibration perception threshold tests were also conducted before and after the vibration intervention. In the gait exams, each of the walking surfaces represented a different tactile stimulus and the vibration intervention included standing on a whole body vibration platform for 60 seconds. Kinematics were collected at 100 Hz with a seven-camera 3-D motion analysis system. Walking surface and vibration intervention were the independent variables. Temporal-spatial gait parameters such as velocity, cadence, step length, and step width were measured. Heel rise occurrence (HR32) and vibration perception threshold (VPT) were also calculated as dependent variables.

Walking surface significantly altered the gait parameter of both TD children and children with ITW. Vibration intervention altered the VPT scores of both TD children and children with ITW. Manipulated surface and excessive vibration may be important in the development of therapeutic/treatment methods for children with Idiopathic Toe Walking. HR32 is a novel calculation designed to distinguish on aspect of the toe-walking gait pattern. It significantly identified toe-walking patterns and quantified

treatment results. Children with ITW appeared to have less toe-walking on the gravel surface. Walking on gravel surface is a potential novel method to reduce toe-walking immediately with no negative after-effects.

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ABBREVIATIONS

ITW	Idiopathic Toe Walking
HR32	Heel rise timing determined by the vertical displacement between the heel marker heights (z coordinates) in static trial (flat-footed) and at 32% (heel rise) of the gait cycle
TD	Typically Developing
VPT	Vibration Perception Threshold
WBV	Whole-body Vibration

CHAPTER 1

REVIEW OF NON-SURGICAL TREATMENTS IN IDIOPATHIC TOE WALKING

Toe-walking, the absence or abnormal pattern of heel contact during the gait cycle, is a common pattern seen in children under three years old. Most toddlers outgrow the condition without intervention (Alvarez, De Vera, Beauchamp, Ward, & Black, 2007; Solan, Kohls-Gatzoulis, & Stephens, 2010; Stricker & Angulo, 1998; Sutherland, Olshen, Cooper, & Woo, 1980). However, the condition may persist in some children. Idiopathic Toe Walking (ITW) is diagnosed when individuals who are older than three years old still walk on the forefoot, with plantarflexed ankle and metatarsalphalangeal joint extension, with no sign of neurological, orthopedic or psychiatric diseases (Eastwood, Menelaus, Dickens, Broughton, & Cole, 2000; Engelbert, Gorter, Uiterwaal, Putte, & Helders, 2011; Hirsch & Wagner, 2004; Sutherland et al., 1980).

The literature presents varied descriptions of the incidence of ITW. Zimbler stated, “The true incidence is unknown but appears to be as high as 5/500 births” (2007). Engelbert et al. found 12% prevalence of ITW among 384 children (2011); whereas, Engstrom found 4.9% total prevalence of ITW among 1436 children (2012). The varied results may be due to the varying criteria for diagnosis among different clinicians, experience with the diagnosis, and/or the difficulty of differentiating between ITW and other toe-walking pathologies.

Prolonged toe-walking gait can cause harmful damage to patients’ health over time. In the short term, patients experience calf muscles soreness/tightness sooner after a period of physical activity compared with typically developing individuals. In the long term, patients are more susceptible to muscle/tendon contracture (Engelbert et al., 2011).

Suggested treatments for the condition include physical therapy, orthotic intervention, serial casting, and orthopedic surgery, depending on the severity of the condition. Generally, the treatments can be categorized into surgical and non-surgical.

Among ITW treatments, surgical treatment is only suggested for patients with failed non-surgical treatment or with more severe conditions (Hemo, Macdessi, Pierce, Aiona, & Sussman, 2006; Stricker & Angulo, 1998). In terms of treatment effectiveness, there is no consensus on which treatment is better than others. Understanding the lack of consensus is complicated by the various treatments, inconsistency in outcome measurement methods, and the nature of the condition.

Typically Developing and ITW Gait

Human walking is a complex, coordinated activity involving simultaneous motion at multiple joints. From a mechanical standpoint, the ankle joint generates the majority of the power that propels the human body forward (Siegel, Kepple, & Stanhope, 2004). More specifically, ankle plantarflexion and dorsiflexion motions are essential to the contribution of efficiency and stability of human gait during stance phase. The ankle absorbs shock at initial contact and generates power to propel the body going forward at pre-swing. The ankle plantarflexes about 5-10 degrees after initial contact and about 30 degrees during pre-swing, (Whittle, 1990).

Human gait can be altered by age, disease, neuromuscular dysfunction, or many other medical conditions (Engelbert et al., 2011; Hicks, Durinick, & Gage, 1988; Marigold & Patla, 2008). A toe-walking pattern is typical among children under the age of three. After three years old, when a mature heel-toe pattern is typically developed, toe-walking may be considered a pathological expression (Alvarez et al., 2007; Armand, Watelain, Roux, Mercier, & Lepoutre, 2007; Stricker & Angulo, 1998; Sutherland et al., 1980). Pathological toe-walking can be a symptom of many diagnoses such as central nervous system disorders, peripheral neurological disorders, peripheral neuromuscular disorders, musculoskeletal disorders, and developmental and pervasive disorders (Engelbert et al., 2011). When the toe-walking gait is a developmental condition, the pattern can disappear along with maturity. However, some ITW conditions can persist and evolve to an ankle motion restriction or a contracture. In Engelbert et al.'s (2011) cross-sectional study on 348 adolescents and young adults, subjects with ITW history were found to have three times higher chance having severe range of motion restriction. Therefore, treatment is recommended for children with ITW.

Results of Treatment Methods

Because the etiology of ITW is still unknown, there is neither a cure nor a definitive treatment for the condition. Instead, there are a variety of treatments available. Since the condition can disappear along with maturity, one treatment option includes observation and vocal cues. However, the success rate is relatively low compared to other treatments in some studies (Eastwood et al., 2000). Other standard methods for treating ITW are physical therapy, serial casting, orthotic treatment, botulinum toxin A injection, and muscle/tendon lengthening surgery. Depending on the severity, the ITW gait patterns vary, and suggested treatments can be different. Surgical treatment is typically done on patients with more severe contracture or skeletal malformation, and non-surgical treatments are typically recommended for mild and moderate conditions.

There has been debate regarding the effectiveness of treatments. Some researchers report that non-surgical treatments improve the condition (Fox, Deakin, Pettigrew, & Paton, 2006); others have concluded that treatments do no better than observation (Deathe & Miller, 2005; Stott, Walt, Lobb, Reynolds, & Nicol, 2004). Few studies have established the effectiveness of any specific treatments for ITW. However, evidence shows that non-surgical treatments can prevent contractures, reduce pain, and promote muscle balance in similar conditions such as cerebral palsy and stroke (Teplicky, Law, & Russell, 2002). Ankle-foot orthoses (AFO) have proven to be beneficial to patients with brain injury to reduce plantarflexion contracture (Blanton, Grissom, & Riolo, 2002). In diplegic cerebral palsy, both solid AFOs and articulated AFOs have been shown to increase stride length, reduce ankle plantarflexion motion, and increase ankle power closer to normal gait in children (Radtka, Skinner, & Johanson, 2005). In a study on gait following stroke, three AFOs (articulated AFO, solid AFO, and dorsiflexion-assist AFO) were tested to determine the effects on plantarflexion contracture. All AFOs were found to be beneficial to patients' dorsiflexion in swing and early stance (Mulroy, Eberly, Gronely, Weiss, & Newsam, 2010).

On the other hand, in a long-term study, Hirsch and Wagner found that the improvements following non-surgical treatments were not significant among children with ITW compared to observation (2004). Sixteen subjects participated in their; eleven of them completed the examination. Videos were taken when the subjects were unobtrusively observed. Videotaping and passive ankle dorsiflexion angle were the outcome measurements for the study. The results suggested that participants still walked on their toes when they were unobtrusively observed, and there was no lasting effect on the passive ankle dorsiflexion angle.

A post-Achilles tendon lengthening surgery study was done a year after surgery. Fifteen subjects with ITW who could not be corrected by non-surgical treatments participated in the study. Computerized gait analysis was used for ankle kinematic and kinetic measurements. Passive dorsiflexion was also assessed. The results showed that Achilles tendon lengthening surgery improved ankle kinematics in patients who failed other treatments. However, the results also showed that ankle power did not achieve normal level at one year after surgery (Hemo et al., 2006).

Studies have indicated the natural history can account for 50% of improvement without any treatment (Eastwood et al., 2000; Engelbert et al., 2011; Stricker & Angulo, 1998). They suggested that non-surgical treatments do not improve the natural history of the condition.

Possible Causes of the Inconsistency

The explanations for the inconsistency of non-surgical treatments can be complicated by many factors. They can be characterized into four categories: variety of measurements, the characteristics of ITW, orthosis design, and etiology of ITW.

1. Variety of measurements

A variety of outcome measurements have been used in ITW studies. Physician- and parent- determined outcomes were commonly used in earlier studies (Eastwood et al., 2000; Fox et al., 2006; Hirsch & Wagner, 2004; Stricker & Angulo, 1998; Teplicky et al., 2002). Some studies used videotape to quantify the functional outcome when participants were unobtrusively observed (Hirsch & Wagner, 2004; Stott et al., 2004). Passive dorsiflexion range of motion is one of the most popular quantitative outcome measurements researchers used throughout the years (Engelbert et al., 2011; Hirsch &

Wagner, 2004; Stott et al., 2004; Stricker & Angulo, 1998). Recently, 3D motion analysis has become a prevalent functional outcome measure in this field (Alvarez et al., 2007; Desloovere et al., 2006; Hemo et al., 2006). Lack of standard, unified, and objective measurements can be one of the causes of the inconsistency. For example, Eastwood et al. used patient and physician-determined outcome measurement on the cast group, and Fox. et al. used passive dorsiflexion on the cast group. Eastwood et al. (2000) found similar results to the observation group, however, Fox et al. (2006) found significant improvement. Having a standard outcome measurement can be helpful to make the studies more meaningful.

2. Characteristics of ITW

Children with ITW often walk on their toes when they are unobtrusively observed. Some research has indicated that the patients only showed improvement when they were being videotaped (Hirsch & Wagner, 2004). Many children with ITW hide their condition when tested in a lab setting (so-called “lab gait”), but walk on their forefoot when they are not watched. It has been a challenge for researchers to collect a child’s natural daily walking pattern in a lab setting. Researchers have tried to avoid “lab gait” by assessing in-home gait using video game console (Stone & Skubic, 2013).

Another challenging characteristic of ITW is in the widely varying levels of severity. Classifying level of severity in ITW is helpful for prescribing treatment. In Alvarez et al.’s study, idiopathic toe walkers were classified into mild, moderate, and severe groups (2007). The patterns for each of the severity groups were: mild, presence of first rocker; moderate, presence of an early third ankle rocker; and severe, predominant early ankle moment. Although the gait pattern of children with ITW is often a combination of the indicators mentioned above, heel rise timing and presence of first rocker are still effective indicators for the classification.

3. Orthosis Design

Orthotic treatment is one of the standard clinical treatments for ITW (Persaud, 2013). Most articulated AFOs used for ITW limit ankle plantarflexion motion, often allowing dorsiflexion but no platarflexion beyond neutral. Because of this constraint, children with ITW can improve their gait pattern by generating heel contact and first ankle rocker. The second ankle rocker can also be improved because some AFOs allow ankle dorsiflexion motion (Desloovere et al., 2006). However, the constraint of plantarflexion motion impedes the functions of shock absorption (loading response) and push off (pre-swing) (Desloovere et al., 2006; Shorter, Kogler, Loth, Durfee, & Hsiao-Wecksler, 2011). It also increases knee flexion at loading response (Mulroy et al., 2010). The plantarflexion-stop based design may not be an ideal option for children with ITW considering they may be musculoskeletally healthy individuals. Assessing the effectiveness of orthotic treatment of ITW is therefore challenged in two ways. First, studies must provide a thorough and accurate description of the orthoses used. Second, comparisons with other treatments should take into account both the positive and negative ramifications on gait introduced by some orthoses.

4. ITW etiology

Although the etiology of ITW remains inconclusive, there are several speculations. Therapists often categorize toe walkers into three categories based on their perceived etiologies. The causes of toe-walking can be problems related to musculoskeletal, neurological-neuromuscular, or sensory processing systems (Persaud, 2013). The physical therapists also believe toe walkers with different etiologies should be treated differently. Few studies have linked ITW to sensory processing dysfunction (SPD), which is diagnosed when an individual cannot integrate the information obtained from sensory systems to organize body movement (Williams, Tinley, & Curtin, 2010). However, there has not been enough substantial evidence to prove the connection. Recently, however, Williams et al. discovered that children with ITW have a significant heightened vibration sensitivity (lower vibration perception threshold) compared to controls (2012). The result supports the idea of a link between ITW and altered sensory processing. Another study done on the neuropsychiatric symptoms among children with ITW indicated that children with ITW as a group have more neuropsychiatric problems compared to typically developing children (Engstrom, Van't Hooft, & Tedroff, 2012). More studies need to be done to confirm the pathology of ITW.

Etiology is a potential confounder for studies related to treatment effectiveness in ITW. If the anecdotal observations of clinicians are correct, a given study of a population of children with ITW might include children who walk on their toes due to low tone alongside children who walk on their toes because they are either hyposensistive or hypersensitive. Children with different etiologies might respond quite differently to certain treatments, introducing an unaccounted-for population variable.

Discussion

To date, there is no conclusive answer to what causes Idiopathic Toe Walking (ITW) or how to best treat the condition. Future studies are needed, not only to determine the cause of toe-walking, but also to compare the effectiveness among treatments and to develop more effective treatments for the condition. For comparing the effectiveness of the treatments, standard 3D motion analysis systems can be used to quantify the improvement of the treatment. To quantify the effectiveness of a treatment, it is essential to capture a natural gait pattern, which is particularly difficult with this population in a laboratory setting.

In developing effective treatments, innovative orthosis design may help patients with toe-walking. The plantarflexion-stop ankle-foot-orthoses (AFO) has been known to impair the first rocker, plantarflexion at loading response, and plantarflexion at pre-swing (Desloovere et al., 2006). An AFO with a stance-control mechanism which allows the ankle to plantarflex at the right timing should be developed to mitigate the drawbacks of the plantarflex-stop mechanism (Fanchiang & Geil, 2013).

Toe-walking can be a consequence of more than one etiology such as sensory process dysfunction, musculoskeletal disorder, or neural dysfunction (Persaud, 2013). Physical therapists have been categorizing toe walkers by their etiologies and developing specific treatment for each of the categories, but the condition remains “idiopathic”. There are still more questions than answers when it comes to etiology of ITW. If sensory processing disorder or dysfunction is one of the etiologies of ITW, are there any ways to train or correct the pathological sensory processing pathways? If musculoskeletal dysfunction is one of the causes, how do we prove the etiology? How do we develop training programs that build patients’ muscle balance in order to correct the problem? If neurological dysfunction is one of the etiologies, can the altered sensitivity be corrected or blocked? These questions need to be addressed before we can greatly improve the effectiveness of non-surgical treatments of ITW.

References

Alvarez, C., De Vera, M., Beauchamp, R., Ward, V., & Black, A. (2007). Classification of idiopathic toe walking based on gait analysis: development and application of the ITW severity classification. *Gait Posture, 26*(3), 428-435. doi: 10.1016/j.gaitpost.2006.10.011

Armand, S., Watelain, E., Roux, E., Mercier, M., & Lepoutre, F. X. (2007). Linking clinical measurements and kinematic gait patterns of toe-walking using fuzzy decision trees. *Gait Posture, 25*(3), 475-484. doi: 10.1016/j.gaitpost.2006.05.014

Blanton, S., Grissom, S., & Riolo, L. (2002). Use of a Static Adjustable Ankle-Foot Orthosis Following Tibial Nerve Block to Reduce Plantar-Flexion Contracture in an Individual With Brain Injury. *Physical Therapy, 82*, 1087-1097.

Deathe, A. B., & Miller, W. C. (2005). The L test of functional mobility: measurement properties of a modified version of the timed "up & go" test designed for people with lower-limb amputations. [Clinical Trial Research Support, Non-U.S. Gov't]. *Phys Ther, 85*(7), 626-635.

Desloovere, K., Molenaers, G., Van Gestel, L., Huenaerts, C., Van Campenhout, A., Callewaert, B., . . . Seyler, J. (2006). How can push-off be preserved during use of an ankle foot orthosis in children with hemiplegia? A prospective controlled study. *Gait Posture, 24*, 142-151.

Eastwood, D. M., Menelaus, M. B., Dickens, D. R., Broughton, N. S., & Cole, W. G. (2000). Idiopathic toe-walking: does treatment alter the natural history? *J Pediatr Orthop B, 9*(1), 47-49.

Engelbert, R., Gorter, J. W., Uiterwaal, C., Putte, E., & Helders, P. (2011). Idiopathic toe-walking in children, adolescents and young adults: a matter of local or generalised stiffness? *BMC Musculoskelet Disord, 12*, 61. doi: 10.1186/1471-2474-12-61

Engstrom, P., & Tedroff, K. (2012). The prevalence and course of idiopathic toe-walking in 5-year-old children. [Research Support, Non-U.S. Gov't]. *Pediatrics, 130*(2), 279-284. doi: 10.1542/peds.2012-0225

Engstrom, P., Van't Hooft, I., & Tedroff, K. (2012). Neuropsychiatric symptoms and problems among children with idiopathic toe-walking. [Research Support, Non-U.S. Gov't]. *J Pediatr Orthop, 32*(8), 848-852. doi: 10.1097/BPO.0b013e31826bec08

Fanchiang, H. D., & Geil, M. D. (2013). *Stance-controlled ankle foot orthosis for Idiopathic Toe Walking.* Paper presented at the 2013 O & P World Congress, Orlando, FL, U.S.A.

Fox, A., Deakin, S., Pettigrew, G., & Paton, R. (2006). Serial casting in the treatment of idiopathic toe-walkers and review of the literature. [Review]. *Acta Orthop Belg, 72*(6), 722-730.

Hemo, Y., Macdessi, S. J., Pierce, R. A., Aiona, M. D., & Sussman, M. D. (2006). Outcome of patients after Achilles tendon lengthening for treatment of idiopathic toe walking. *J Pediatr Orthop, 26*(3), 336-340. doi: 10.1097/01.bpo.0000217743.44609.44

Hicks, R., Durinick, N., & Gage, J. R. (1988). Differentiation of idiopathic toe-walking and cerebral palsy. *J Pediatr Orthop, 8*(2), 160-163.

Hirsch, G., & Wagner, B. (2004). The natural history of idiopathic toe-walking: a long-term follow-up of fourteen conservatively treated children. *Acta Paediatr, 93*(2), 196-199.

Marigold, D. S., & Patla, A. E. (2008). Age-related changes in gait for multi-surface terrain. [Comparative Study Research Support, Non-U.S. Gov't]. *Gait Posture, 27*(4), 689-696. doi: 10.1016/j.gaitpost.2007.09.005

Mulroy, S. J., Eberly, V. J., Gronely, J. K., Weiss, W., & Newsam, C. J. (2010). Effect of AFO design on walking after stroke: impact of ankle plantar flexion contracture. [Comparative Study Research Support, U.S. Gov't, Non-P.H.S.]. *Prosthet Orthot Int, 34*(3), 277-292. doi: 10.3109/03093646.2010.501512

Persaud, L. M. (2013). Evaluation & Management of Pediatric Toe Walking from PT & OT Perspectives. Telluride, Colorado: Progressive GaitWays, LLC.

Radtka, S. A., Skinner, S. R., & Johanson, M. E. (2005). A comparison of gait with solid and hinged ankle-foot orthoses in children with spastic diplegic cerebral palsy. [Comparative Study Research Support, Non-U.S. Gov't]. *Gait Posture, 21*(3), 303-310. doi: 10.1016/j.gaitpost.2004.03.004

Shorter, K. A., Kogler, G. F., Loth, E., Durfee, W. K., & Hsiao-Wecksler, E. T. (2011). A portable powered ankle-foot orthosis for rehabilitation. [Research Support, U.S. Gov't, Non-P.H.S.]. *J Rehabil Res Dev, 48*(4), 459-472.

Siegel, K. L., Kepple, T. M., & Stanhope, S. J. (2004). Joint moment control of mechanical energy flow during normal gait. *Gait Posture, 19*(1), 7.

Solan, M. C., Kohls-Gatzoulis, J., & Stephens, M. M. (2010). Idiopathic toe walking and contractures of the triceps surae. [Review]. *Foot Ankle Clin, 15*(2), 297-307. doi: 10.1016/j.fcl.2010.01.002

Stone, E., & Skubic, M. (2013). Unobtrusive, Continuous, In-Home Gait Measurement Using the Microsoft Kinect. *IEEE Trans Biomed Eng*. doi: 10.1109/TBME.2013.2266341

Stott, N. S., Walt, S. E., Lobb, G. A., Reynolds, N., & Nicol, R. O. (2004). Treatment for idiopathic toe-walking: results at skeletal maturity. [Research Support, Non-U.S. Gov't]. *J Pediatr Orthop, 24*(1), 63-69.

Stricker, S. J., & Angulo, J. C. (1998). Idiopathic toe walking: a comparison of treatment methods. [Comparative Study]. *J Pediatr Orthop, 18*(3), 289-293.

Sutherland, D. H., Olshen, R., Cooper, L., & Woo, S. L. (1980). The development of mature gait. *J Bone Joint Surg Am, 62*(3), 336-353.

Teplicky, R., Law, M., & Russell, D. (2002). The Effectiveness of Casts, Orthoses, and Splints for Children with Neurological Disorders. *Infants and Young Children 15*(1), 42-50.

Whittle, M. W. (1990). *GAIT ANALYSIS: AN INTRODUCTION* (4th ed.). Philadelphia: Heidi Harrison.

Williams, C. M., Tinley, P., & Curtin, M. (2010). Idiopathic toe walking and sensory processing dysfunction. *J Foot Ankle Res, 3*, 16. doi: 10.1186/1757-1146-3-16

Williams, C. M., Tinley, P., Curtin, M., & Nielsen, S. (2012). Vibration perception thresholds in children with idiopathic toe walking gait. [Research Support, Non-U.S. Gov't]. *J Child Neurol, 27*(8), 1017-1021. doi: 10.1177/0883073811432748

Zimbler, S. (2007). idiopathic Toe Walking: Current Evaluation and Management. *Orthopaedic Journal of Havard Medicine School*, 3.

CHAPTER 2

THE EFFECTS OF WALKING SURFACE ON THE GAIT PATTERN AND HEEL RISE EVENT TIMING OF TYPICALLY DEVELOPING CHILDREN

Human gait can be altered by age, disease, neuromuscular dysfunction, or many other physiological/biomechanical conditions (Engelbert, Gorter, Uiterwaal, Putte, & Helders, 2011; Hicks, Durinick, & Gage, 1988; Marigold & Patla, 2008). As gait matures, toddlers change from a toe-walking pattern to heel-toe-walking pattern. In general, typically developing children achieve a heel to toe pattern before the age of three years old (Alvarez, De Vera, Beauchamp, Ward, & Black, 2007; Perry & Burnfield, 2010; Solan, Kohls-Gatzoulis, & Stephens, 2010; Stricker & Angulo, 1998; Sutherland, Olshen, Cooper, & Woo, 1980). After three years old, typically developing children keep developing their gait pattern until 11 years old (Hausdorff, Zemany, Peng, & Goldberger, 1999; Hillman, Stansfield, Richardson, & Robb, 2009).

Few studies have investigated the gait pattern changes altered by surfaces in developing children. Lu et al. studied obstacle-crossing in young and older adults (2006). They focused on the effects of age. Marigold and Patla investigated adapting locomotion to surface change in young and older adults (2008). They used multi-surface terrain to find the variation cause by age. Joh et al. and Adolph et al. studied the effects of surface friction to human locomotion in adults and infants. The surfaces in their studies were the surfaces with low-, medium-, and high-friction (Adolph, Joh, & Eppler, 2010; Joh, Adolph, Narayanan, & Dietz, 2007).

The current study investigated the effects of altered surface on the gait pattern of typically developing children. Children encounter multiple surfaces and terrains in daily life. For example, in a single school day a child might encounter hardwood and carpet at home, concrete and asphalt at school, and gravel, grass, and mulch as play. However, the analysis of normal gait in children has focused on laboratory-based smooth even surfaces. Furthermore, many pathological symptoms are discovered and treated during childhood. Establishing the role of varied terrains in normal walking is important for future understanding of walking surface in pathological gait patterns. Certain pathologies, such as Idiopathic Toe Walking or toe walking associated with Autism, may have a sensory basis for which walking surface could be connected. It is difficult to study this connection without a baseline. Therefore, the purpose of this study is to establish understanding of the normal kinematics of typically developing children on multiple walking surfaces. With an eye toward future studies of sensory-related gait disorders, this study focuses on the timing of the heel rise event in the gait cycle, which might have important implications on plantar foot sensation during the gait cycle (Fanchiang & Geil, 2013). The study measured temporal and spatial parameters of gait with a focus on the timing of the heel rise event, which indicates the onset of third rocker (Perry & Burnfield, 2010). This study tested the following hypotheses: 1. Participants will show different velocity, cadence, step length, and step width on different walkways. 2. Participants will show different heel rise timing on various walkways.

Methods

The study is an analysis of motion data collected from typically developing (TD) children, aged from 4 to 10 years old, and assessed at Georgia State University (GSU)

Biomechanics Laboratory. The participant recruitment was based on a referral system. Elementary school teachers provide information to their students. Potential participants then contacted us. Qualified participants were recruited for the current study. Exclusion criteria included history of neuromotor or musculoskeletal disorders, unresolved orthopedic injury, or other inability to walk through a distance of 12 m approximately 30 times. Before any participant was recruited, the protocols were approved by the GSU Institutional Review Board (IRB). Once participant and his/her parent arrived, parent signed parental permission forms and participants of appropriate age signed or verbally acknowledged informed assent. The experiment took approximately 45 minutes including participant preparation, and a gait examination.

The following demographic/anthropometric data were collected for each participant: date of birth, onset of walking, family history of ITW, height, weight, knee width, ankle width, and leg length. The gait exam involved each participant walking barefooted ten times at a comfortable self-selected walking speed over each of the three 4-meter walkways with different surfaces. Each of the surfaces – firm vinyl tile, pile carpet, and loose pea gravel -- offers a different tactile stimulus to the participants. The vinyl tile provided a firm even surface. The pile carpet provided a compliant sensation. The thickness of the carpet before force applied was 18mm, after force applied was 6mm. Loose gravel represented an uneven surface. The average rock-diameter was 13mm, standard deviation was 4mm. Because the thickness of the surface, each walkway had a different height; carpet was 18mm; vinyl tile was 0mm; gravel was approximately 40mm.

A seven-camera Vicon motion analysis system (OMG, Oxford, England) tracked the motion of fifteen reflective markers. Kinematic data were collected using Vicon

Nexus software version 1.8 (OMG, Oxford, England). For each of the participants, ten trials for each walkway were processed for further analyses.

Spatiotemporal parameters, i.e., velocity, cadence, step length, and step width were extracted from the kinematic data using Vicon Polygon software version 3 (OMG, Oxford, England). Besides the parameters mentioned above, in current study, we studied the timing of the heel rise. Early heel rise is an indicator of potential gait abnormities (Alvarez et al., 2007). In particular, early heel rise may be associated with gait disorders that arise from sensory processing dysfunction. Individuals who are hypersensitive might use early heel rise to reduce sensory input via the plantar surface of the foot (Fanchiang & Geil, 2013). On the contrary, individuals who are hyposensitive might use a pattern similar to toe-walking in which early heel rise increases forefoot pressure. Understanding these patterns requires establishment of baseline heel rise information in children walking on multiple terrains.

Normal third ankle rocker occurs between heel rise (32 % of gait cycle) and toe off (60% of gait cycle) (Perry & Burnfield, 2010; Whittle, 1990). Therefore, an early third rocker is when the heel rise event happens earlier than 32% of the gait cycle. Because the heel marker is attached to participant's heel. During mid-stance, when the foot is flat to the ground, the heel marker height stays the same; when heel rise happens, the heel marker height rises regardless the walking patterns (Figure 1). Therefore, an increase in heel marker height above baseline at 32% of the gait cycle is an indication of early heel rise event. Furthermore, both typically developing and pathological gait patterns show positive slopes on their heel marker height graph from heel rise to mid-swing, due to forward and upward body movement. Therefore, the greater the heel marker height at 32% of the gait cycle suggests the earlier heel rise event occurrence. In the current study, heel rise was assessed by determining the heel marker height at 32% of the gait cycle (HR32). HR32 was measured as the difference between the heel marker z coordinate in a static flat-footed trial (Z_i) and the z coordinate at 32% of the gait cycle (Z_f) (Figure 2). The greater the Z_f results the greater HR32, which indicates an early heel rise. The Z_f and Z_i were acquired using both Vicon Polygon software and a custom Matlab (The Mathworks, Inc., Natrick, MA) program.

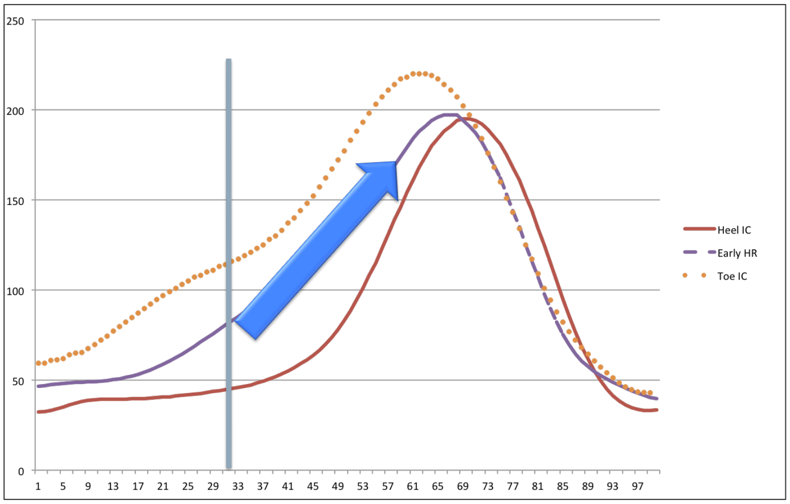

Figure 1 Heel Marker Height

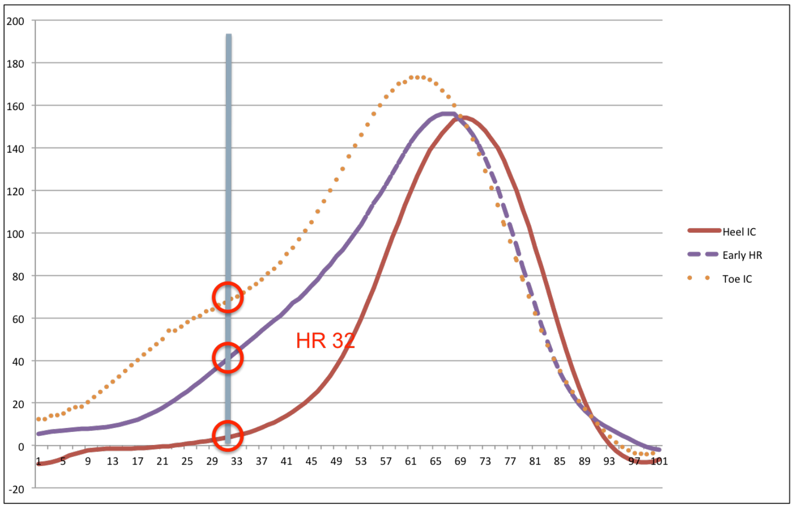

Figure 2 HR32

Protocols

The following demographic/anthropometric data were collected for each participant: date of birth, onset of walking, height, weight, knee width, ankle width, and leg length. Each participant then quietly played in the lab for 15 minutes to reduce any potential environmental impact (Williams, Tinley, Curtin, & Nielsen, 2012). Next, we placed a spherical 15mm-diameter reflective marker on each heel at the height of the second metatarsal head. To determine temporal and spatial parameters additional markers were placed over key landmarks on each participant's lower extremity according to the Vicon Plug-In-Gait Lower limb Sacrum model (Figure 3).

A static Plug-In-Gait trial was collected while each participant performed a T-pose (arms abducted) with his/her frontal plane parallel to the x-axis of the system on each walkway. The Static Plug-In-Gait trial was assessed to establish a baseline heel marker height for each of the walkways.

Participants then walked at a comfortable self-selected speed in a random sequence over the walkways (1, 2, or 3; Figure 4). Thirty trials in total were collected during the gait exam for each participant, ten on each surface.

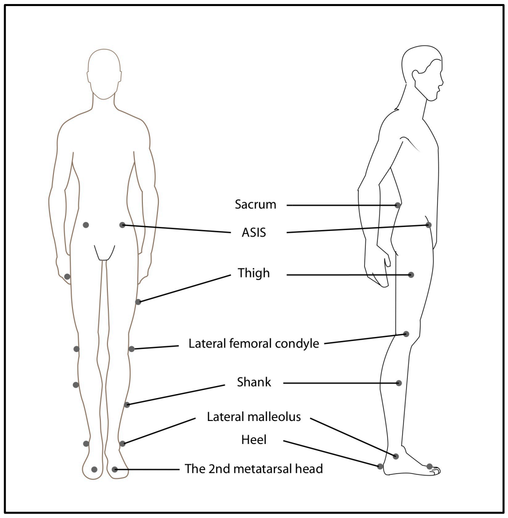

Figure 3 Vicon Plug-In-Gait Lower Limb Sacrum Model Landmarks

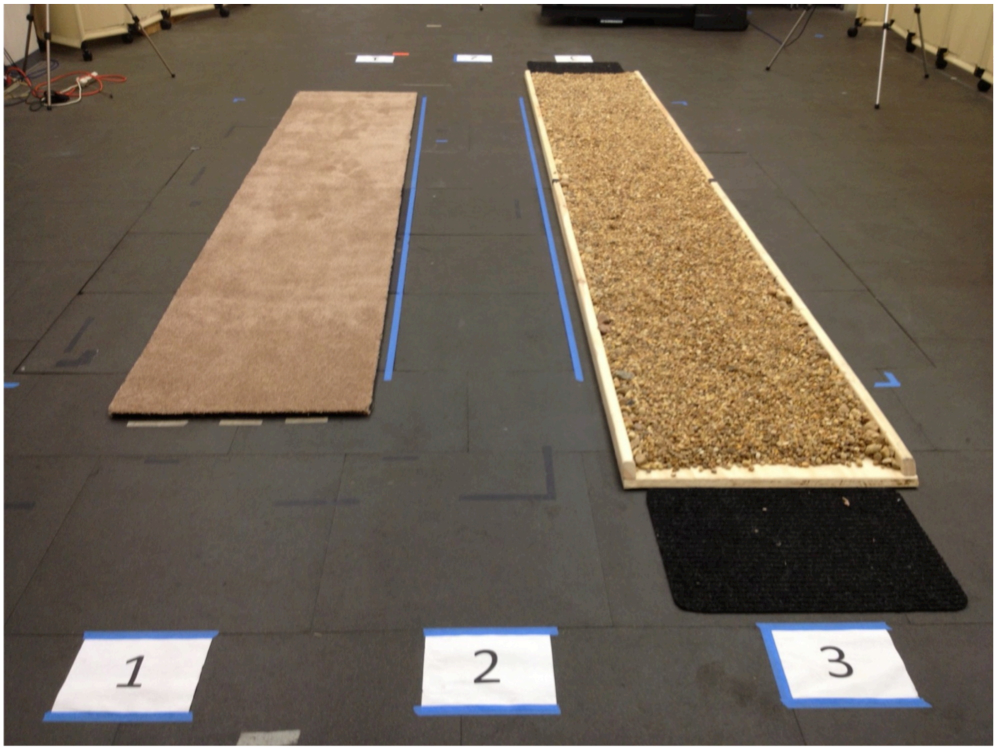

Figure 4 4-meter Walkways
1: Pile Carpet; 2: Vinyl Tile; 3: Loose Gravel.

Statistical Analysis

Five factorial analyses of variance (ANOVAs) with repeated measures were used to analyze the following dependent variables: velocity, cadence, step length, step width, and HR32. The within-subject variable was surface: 1. Pile carpet; 2. Vinyl tile; 3. Loose gravel. The mean and standard deviation of dependent variables were calculated for each condition. The α-level was set as 0.05. When the test showed the statistical significance, the paired comparisons were performed between the conditions with Bonferroni adjustments. Finally, a test was conducted to determine any effects of gait development by dividing the participants into two groups, one younger than 7 years and the other older than age 7, and comparing between groups on each surface. All statistical procedures were performed with the SPSS system (International Business Machines Corp., New Orchard Road, Armonk, NY 10504).

Results

Fifteen participants completed the study. The average age, height, and weight were 7.8 years old (SD= 1.5), 1.3 m (SD= .12), and 29.1 kg (SD=9.0) (Table 1). Eighty percent of the participants had hardwood floors in their household and 53% of them had carpeted floors. During the recruitment, a participant dropped out before any data was collected because she did not want to walk on the gravel surface. It was not because the gravel walkway was harmful. He/her did not show any pain walking on gravel surface during reducing environmental impact period. We speculated that she was uncomfortable of being watched.

Walking surface altered the gait pattern. Velocity, cadence, and step length were significantly different among surfaces ($P < 0.001$). HR32 was significantly different among surface conditions ($P = 0.033$). Step width was not significantly different among surface conditions ($P = 0.67$) (Table 2).

Group	Gender	Age (year)	Height (cm)	Weight (kg)
TD	Female	7	118	20.7
TD	Male	9	130	26.8
TD	Male	7	125	23.1
TD	Female	8	142	36.2
TD	Male	9	127	37.8
TD	Female	5	111	17.2
TD	Female	10	145	33.4
TD	Female	9	137	24.8
TD	Male	9	143	44.6
TD	Male	8	144	45.7
TD	Female	8	130	29.2
TD	Female	7	121	22.9
TD	Female	5	106	16.8
TD	Male	9	134	31.8
TD	Male	7	127	25.2
TD MEAN		7.8 (1.5)	130 (12)	29.1 (9)

Table 1 *Participant Description (TD)*

	Pile Carpet		Vinyl tile		Loose gravel		*P*-value
	Mean	SD	Mean	SD	Mean	SD	
Velocity (m/s)	1.11	0.12	1.15	0.12	0.74	0.16	<0.001*
Cadence (step/min)	125	13	130	14	109	13	<0.001*
Step length (m)	0.54	0.04	0.53	0.04	0.41	0.08	<0.001*
Step width(m)	0.12	0.03	0.11	0.03	0.11	0.03	0.67
HR32(mm)	20	11	14	12	12	5	0.033*

Table 2 *TD Statistical Analysis Summary* (N=15). * Indicates statistical significance

After pairwise comparison with Bonferroni adjustments, we found that walking speed on gravel was significantly slower than walking on carpet ($P < 0.001$) and vinyl tile ($P < 0.001$) surfaces. Walking on carpet was also significantly slower than walking on vinyl tile surface ($P = 0.036$). In cadence, walking on every walkway was significantly different than other walkways ($P < 0.001$). Walking on vinyl tile had the highest cadence and walking on gravel had the lowest cadence. In step length, walking on gravel had significantly shorter step length than walking on carpet ($P < 0.001$) and vinyl tile ($P < 0.001$) walkways. In HR32, walking on carpet had significant higher HR32 than walking on vinyl tile ($P < 0.001$). Between walking on carpet and gravel, HR32 was approaching significance ($P = 0.06$) (Table 3). Independent t-tests between the age groups (<7 years vs. >7 years) revealed no significant differences based on gait development on any surface.

	Carpet vs. Vinyl tile	Vinyl tile vs. Gravel	Carpet vs. Gravel
Velocity	0.04*	<0.001*	<0.001*
Cadence	<0.001*	<0.001*	<0.001*
Step Length	0.75	<0.001*	<0.001*
HR32	<0.001*	1.53	0.06

Table 3 *P-value of the Pairwise Comparisons with Bonferroni Adjustments*
*Indicates statistical significance

Discussion

The study tested the hypothesis of whether typically developing (TD) children walked differently and whether they had different heel rise timing on three walking surfaces. The walking surfaces in the current study were the surfaces that people commonly encounter. However, the effects of surface on the gait pattern were poorly understood. Comparing the gait patterns of participants walking on different surfaces helped us understand whether different sensations of the surfaces change how children walk.

The study was designed to assess a broad age range, but the breadth might be a limitation if differences are noted between the younger and older participants. However, no significant difference was found between groups when the participants were divided into groups younger than and older than 7 years. We used 7 years old as a cutoff according to Hausdorff el al.'s findings (1999). The current study only assessed comfortable, self-selected walking speed. Various velocities are suggested to be tested in future studies, anticipating that speed might alter the influence of surface on gait. The force platform was not available on carpet and gravel surfaces; therefore, kinetic data were not collected in the current study. The gait exams were conducted under barefoot condition, limiting our ability to generalize results to shod walking conditions.

Walking on different surfaces significantly altered the following gait kinematics: velocity, cadence, step length, and heel rise. When children walked on carpet, they showed longer step length and earlier heel rise. When they walked on vinyl tile, they showed faster velocity and higher cadence. When they walked on gravel, they showed slower velocity, lower cadence, and shorter step length. The participants also showed significant higher HR32 on carpet comparing to vinyl tile. This result indicated that walking on carpet produced an earlier heel rise event. The changes in gait pattern may be due to various self-selected walking speeds. In Stansfield et al.'s gait velocity study, they stated that height and weight have minimal influence on gait parameters (2006). On the other hand, gait velocity has significant influence on many kinematic parameters in sagittal, frontal, and transverse planes (Schwartz, Rozumalski, & Trost, 2008). Knowing velocity is a prominent factor to gait pattern, and ability to decouple stride frequency from walking speed is an important indication of changed gait pattern (Osaki, Kunin, Cohen, & Raphan, 2008). Research with controlled walking speeds on more surfaces and barefoot and shot walking trials are recommended. The level of difficulty of the surfaces can also contribute the changes in gait pattern. Therefore, participants walked slower and took shorter steps on more challenging condition, in this case, the gravel surface. For walking on more challenging surface, we expected the step width to be greater on gravel surface. However, we did not find significantly increased step width across the surfaces. Participants adjusted their gait pattern to compensate the challenge of the surfaces by altering velocity, cadence, and step length, but not step width. Perhaps, the challenge of the surfaces was not great enough to affect the balance; therefore, we did not find significant increase of step width. In a multi-surface terrain study, Marigold and Patla found multi-surface terrain poses a greater challenge to balance reflected by the increased variability (2008). We found a similar pattern in the current study when participants walked on gravel walkway. They showed higher variability on walking velocity (SD= .16) and step length (SD= .08). In kinetics, although we did not have force platforms underneath the surfaces, we assumed that carpet and vinyl surfaces had different rates of shock absorption. Therefore, the impact of the ground reaction force that participants felt on each surface may have varied. Avoiding the impact of ground reaction force can be a possible cause of the observed gait pattern changes.

TD children changed their walking pattern accordingly to the surface change. The change of the walking pattern may be due to various sets and/or sequences of muscles were activated. Understanding the effects of surface to developing human gait may be important to human walking throughout life span. Because the sensations given by the surfaces were very different, we clearly observed that how the surface were felt changed how people walk. The next step of this line of research would be to test whether less different surfaces still have similar gait pattern. The mechanisms of how walking surface altered sensory processing pathways were not explained in the scope of the current study. Were the mechanisms psychological, neurological, or related to sensory processing dysfunction? Collaboration with researchers in other field such as neurology, biology, or psychology will be helpful to solve the anecdote.

References

Adolph, K. E., Joh, A. S., & Eppler, M. A. (2010). Infants' perception of affordances of slopes under high- and low-friction conditions. [Research Support, N.I.H., Extramural]. *J Exp Psychol Hum Percept Perform, 36*(4), 797-811. doi: 10.1037/a0017450

Alvarez, C., De Vera, M., Beauchamp, R., Ward, V., & Black, A. (2007). Classification of idiopathic toe walking based on gait analysis: development and application of the ITW severity classification. *Gait Posture, 26*(3), 428-435. doi: 10.1016/j.gaitpost.2006.10.011

Engelbert, R., Gorter, J. W., Uiterwaal, C., Putte, E., & Helders, P. (2011). Idiopathic toe-walking in children, adolescents and young adults: a matter of local or generalised stiffness? *BMC Musculoskelet Disord, 12*, 61. doi: 10.1186/1471-2474-12-61

Fanchiang, H. D., & Geil, M. D. (2013). *Motion analysis of children with idiopathic toe walking and controls on three terrains with vibration intervention*. Paper presented at the GAIT & CLINICAL MOVEMENT ANALYSIS SOCIETY 2013 ANNUAL CONFERENCE, Cincinnati, OH.

Hausdorff, J. M., Zemany, L., Peng, C., & Goldberger, A. L. (1999). Maturation of gait dynamics: stride-to-stride variability and its temporal organization in children. [Clinical Trial Research Support, Non-U.S. Gov't Research Support, U.S. Gov't, Non-P.H.S. Research Support, U.S. Gov't, P.H.S.]. *J Appl Physiol (1985), 86*(3), 1040-1047.

Hicks, R., Durinick, N., & Gage, J. R. (1988). Differentiation of idiopathic toe-walking and cerebral palsy. *J Pediatr Orthop, 8*(2), 160-163.

Hillman, S. J., Stansfield, B. W., Richardson, A. M., & Robb, J. E. (2009). Development of temporal and distance parameters of gait in normal children. [Research Support, Non-U.S. Gov't]. *Gait Posture, 29*(1), 81-85. doi: 10.1016/j.gaitpost.2008.06.012

Joh, A. S., Adolph, K. E., Narayanan, P. J., & Dietz, V. A. (2007). Gauging possibilities for action based on friction underfoot. [Research Support, N.I.H., Extramural Research Support, Non-U.S. Gov't]. *J Exp Psychol Hum Percept Perform, 33*(5), 1145-1157. doi: 10.1037/0096-1523.33.5.1145

Lu, T. W., Chen, H. L., & Chen, S. C. (2006). Comparisons of the lower limb kinematics between young and older adults when crossing obstacles of different heights. [Comparative Study]. *Gait Posture, 23*(4), 471-479. doi: 10.1016/j.gaitpost.2005.06.005

Marigold, D. S., & Patla, A. E. (2008). Age-related changes in gait for multi-surface terrain. [Comparative Study Research Support, Non-U.S. Gov't]. *Gait Posture, 27*(4), 689-696. doi: 10.1016/j.gaitpost.2007.09.005

Osaki, Y., Kunin, M., Cohen, B., & Raphan, T. (2008). Relative contribution of walking velocity and stepping frequency to the neural control of locomotion. [Comparative Study]. *Exp Brain Res, 185*(1), 121-135. doi: 10.1007/s00221-007-1139-1

Perry, J., & Burnfield, J. M. (2010). *GAIT ANALYSIS: Normal and Pathological Function* (2nd ed.). Thorofare: SLACK Incorporated.

Schwartz, M. H., Rozumalski, A., & Trost, J. P. (2008). The effect of walking speed on the gait of typically developing children. *J Biomech, 41*(8), 1639-1650. doi: 10.1016/j.jbiomech.2008.03.015

Solan, M. C., Kohls-Gatzoulis, J., & Stephens, M. M. (2010). Idiopathic toe walking and contractures of the triceps surae. [Review]. *Foot Ankle Clin, 15*(2), 297-307. doi: 10.1016/j.fcl.2010.01.002

Stansfield, B. W., Hillman, S. J., Hazlewood, M. E., & Robb, J. E. (2006). Regression analysis of gait parameters with speed in normal children walking at self-selected speeds. [Research Support, Non-U.S. Gov't]. *Gait Posture, 23*(3), 288-294. doi: 10.1016/j.gaitpost.2005.03.005

Stricker, S. J., & Angulo, J. C. (1998). Idiopathic toe walking: a comparison of treatment methods. [Comparative Study]. *J Pediatr Orthop, 18*(3), 289-293.

Sutherland, D. H., Olshen, R., Cooper, L., & Woo, S. L. (1980). The development of mature gait. *J Bone Joint Surg Am, 62*(3), 336-353.

Whittle, M. W. (1990). *GAIT ANALYSIS: AN INTRODUCTION* (4th ed.). Philadelphia: Heidi Harrison.

Williams, C. M., Tinley, P., Curtin, M., & Nielsen, S. (2012). Vibration perception thresholds in children with idiopathic toe walking gait. [Research Support, Non-U.S. Gov't]. *J Child Neurol, 27*(8), 1017-1021. doi: 10.1177/0883073811432748

CHAPTER 3

THE EFFECTS OF WALKING SURFACE ON THE GAIT PATTERN OF CHILDREN WITH IDIOPATHIC TOE WALKING

Toe-walking, the absence of heel contact during the gait cycle, is a common pattern seen in children under three years old, but most toddlers outgrow the condition (Alvarez, De Vera, Beauchamp, Ward, & Black, 2007; Solan, Kohls-Gatzoulis, & Stephens, 2010; Stricker & Angulo, 1998; Sutherland, Olshen, Cooper, & Woo, 1980). However, the condition may persist in some children. Idiopathic Toe Walking (ITW) is diagnosed when individuals who are older than three years still walk on their toes with no sign of neurological, orthopedic or psychiatric diseases (Eastwood, Menelaus, Dickens, Broughton, & Cole, 2000; Engelbert, Gorter, Uiterwaal, Putte, & Helders, 2011; Hirsch & Wagner, 2004; Sutherland et al., 1980).

The incidence reports of ITW in the literature are widely varied. Zimbler stated, “The true incidence is unknown but appears to be as high as 5/500 births” (2007). Engelbert et al. found 12% prevalence of ITW among 384 children (2011); whereas, Engstrom found 4.9% total prevalence of ITW among 1436 children (2012). The varied results may be due to the personal experience of the clinician and/or the difficulty of differentiating ITW from other toe-walking pathologies.

Prolonged toe-walking gait can cause harmful damage to patients’ health over time. In the short term, patients experience soreness and tightness of ankle plantarflexors sooner after a period of physical activity compared to typically developed individuals. In the long term, patients are more susceptible to muscle/tendon contracture (Engelbert et al., 2011). Generally, treatments for prolonged toe walking can be categorized into surgical and non-surgical. Depending on the severity of the condition, patients receive orthotic treatment, serial casting, botulinum toxin A injection, or muscle/tendon lengthening surgery (Hemo, Macdessi, Pierce, Aiona, & Sussman, 2006; Stricker & Angulo, 1998). Even though there is no consensus on which treatment is better than others, many clinicians report, at least anecdotally, that ITW is not rare in children, and it needs to be treated.

With uncertainty concerning the effectiveness of ITW treatments, researchers have taken different approaches to understand the etiology and develop potential alternative treatments. Recently, some research has linked ITW to sensory processing dysfunction, which is diagnosed when an individual cannot integrate the information obtained from sensory systems to organize body movement (Williams, Tinley, & Curtin, 2010). A recent study discovered that children with ITW have a significantly heightened vibration sensitivity (lower vibration perception threshold) compared to controls (Williams, Tinley, Curtin, & Nielsen, 2012). Another study was done on the neuropsychiatric symptoms among children with ITW indicated that children with ITW as a group have more neuropsychiatric problems compared to typically developing children (Enqstrom, Van't Hooft, & Tedroff, 2012). Both studies suggest that neurological disorder can be one of the etiologies of ITW.

Studies have shown that human gait can be altered by age, disease, neuromuscular dysfunction or many other conditions (Engelbert et al., 2011; Hicks, Durinick, & Gage, 1988; Marigold & Patla, 2008). If sensory processing is involved in some children who toe-walk, then tactile and somatosensory alterations associated with the walking surface might influence gait patterns differently than they do in typically developing children. Moreover, if a particular walking surface is found that reduces or eliminates toe walking, it could be used as a novel treatment modality. Given the possible difference in vibration perception in children with ITW, and the anecdotal observations of a number of therapists, the possibility exists that children may choose to walk on their toes because they are either hyposensitive or hypersensitive. Ironically, a similar kinematic pattern could result from these two opposite sensory processing extremes. Sensory-seeking children may adopt a staccato toe-strike pattern to increase pressure on the forefoot and to increase the transmission of vibration through the body. Sensory-avoiding children may choose an equinus pattern, or an early heel rise pattern, simply to limit the area of the foot receiving tactile stimulus.

The current study investigated the effects of walking surface on the gait pattern of children with ITW. Children encounter multiple surfaces and terrains in daily life. For example, in a single school day a child might encounter hardwood and carpet at home, concrete and asphalt at school, and gravel, grass, and mulch as play. However, the analysis of normal gait in children has focused on laboratory-based smooth even surfaces. Furthermore, many pathological symptoms are discovered and treated during childhood. Establishing the role of varied terrains in normal walking and pathological walking is important for future understanding of walking surface in pathological gait patterns. Certain pathologies, such as ITW or toe walking associated with Autism, may have a sensory basis for which walking surface could be connected. It is difficult to study this connection without a comparison between normal walking and pathological walking. Therefore, the purpose of this study is to establish understanding of the kinematics of typically developing children and children with ITW on multiple walking surfaces.

The study measured temporal and spatial parameters of gait with a focus on the timing of the heel rise event, which indicates the onset of third rocker (Perry & Burnfield, 2010). In our experience, the timing of the heel rise event is a valuable indicator of altered gait in children with ITW (Fanchiang & Geil, 2013). Because many children with ITW maintain adequate ankle range of motion for some time, they are capable of achieving normal standing and normal heel contact in gait. When they are observed, as in a laboratory setting, many exhibit far more heel-to-toe gait than they do in settings that are more customary to them. Despite these apparently “normal” steps, we have learned that early heel rise still occurs in most (Herrin & Geil, 2013). Consequently, this study tested the following hypotheses: 1. All children will show different temporal and spatial parameters on different walking surfaces, 2. The effect will be different in children with ITW vs. typically developing children, and 3. Timing of the heel rise event will be different between the study groups, regardless of walking surface.

Methods

The study was an analysis of motion data collected from children with Idiopathic Toe Walking (ITW) and age-matched typically developing (TD) controls, aged from 4 to 10 years old, and assessed at the Georgia State University (GSU) Biomechanics Laboratory. The participant recruitment was based on a referral system. Physical therapists provided information to children with ITW who were interested in participating. Potential TD participants were referred from elementary schools around metro Atlanta. Qualified participants were recruited for the current study. Exclusion criteria included history of neuromotor or musculoskeletal disorders, unresolved orthopedic injury, or other inability to walk through a distance of 12 m approximately 30 times. Before any participant was recruited, the protocols were approved by the GSU Institutional Review Board (IRB). Before the study started, each child's parent signed parental permission forms and participants of appropriate age signed or verbally acknowledged informed assent. The experiment took approximately 45 minutes including participant preparation, and a gait examination.

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A seven-camera Vicon motion analysis system (OMG, Oxford, England) tracked the motion of fifteen reflective markers. Kinematic data were collected using Vicon Nexus software version 1.8 (OMG, Oxford, England). For each of the participants, ten trials for each walkway were processed for further analyses.

Spatiotemporal parameters, i.e., velocity, cadence, step length, and step width were extracted from the kinematic data using Vicon Polygon software version 3 (OMG, Oxford, England). Besides the parameters mentioned above we studied the timing of the timing of the heel rise. Early heel rise is an indicator of potential gait abnormities (Alvarez et al., 2007). Alvarez et al. categorized toe-walking into three severity classes: mild (presence of first rocker), moderate (presence of an early third ankle rocker), and severe (predominant early ankle moment). The classification methods have illustrated the characteristics of ITW; but to quantify toe-walking pattern across all severity levels, a new measure is needed. A measure not only differentiates TD and ITW walking patterns, but also quantifies the severity of toe-walking.

Normal third ankle rocker occurs between heel rise (32 % of gait cycle) and toe off (60% of gait cycle) (Perry & Burnfield, 2010; Whittle, 1990). Therefore, an early third rocker is when the heel rise event happens earlier than 32% of the gait cycle. Because the heel marker is attached to participant's heel. During mid-stance, when the foot is flat to the ground, the heel marker height stays the same; when heel rise happens, the heel marker height rises regardless the severity (Figure 5). Therefore, an increase in heel marker height above baseline at 32% of the gait cycle is an indication of early heel rise event. Furthermore, both typically developing children and children with ITW show positive slopes on their heel marker height graph between heel rise to mid-swing, due to forward and upward body movement. Therefore, the greater the heel marker height at 32% of the gait cycle suggests the earlier heel rise event occurrence. In the current study, heel rise was assessed by determining the heel marker height at 32% of the gait cycle (HR32). HR32 was measured as the difference between the heel marker z coordinate in a static flat-footed trial (Z_i) and the z coordinate at 32% of the gait cycle (Z_f) (Figure 6). The greater the Z_f results the greater HR32, which indicates an early heel rise. The Z_f and Z_i were acquired using both Vicon Polygon software and a custom Matlab (The Mathworks, Inc., Natrick, MA) program.

Protocols

The following demographic/anthropometric data were collected for each participant: date of birth, onset of walking, family history of ITW, height, weight, knee width, ankle width, and leg length. Each participant then quietly played in the lab for 15 minutes to reduce any potential environmental impact (Williams et al., 2012). Next, we placed a spherical 15mm-diameter reflective marker was placed on each heel at the height of the second metatarsal head. To determine temporal and spatial parameters additional markers were placed over key landmarks on each participant's lower extremity according to the Vicon Plug-In-Gait Lower limb Sacrum model.

A static Plug-In-Gait trial was collected while each participant performed a T-pose (arms abducted) with his/her frontal plane parallel to the x-axis of the system on each walkway. The Static Plug-In-Gait trial was assessed to establish a baseline heel marker height for each of the walkways.

Participants then walked at a comfortable self-selected speed in a random sequence over the walkways (1, 2, or 3; Figure 7). Thirty trials in total were collected during the gait exam for each participant, ten on each surface.

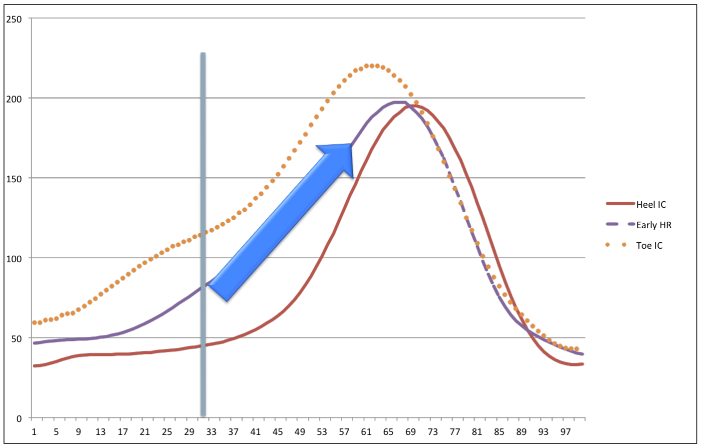

Figure 5 Heel Marker Height

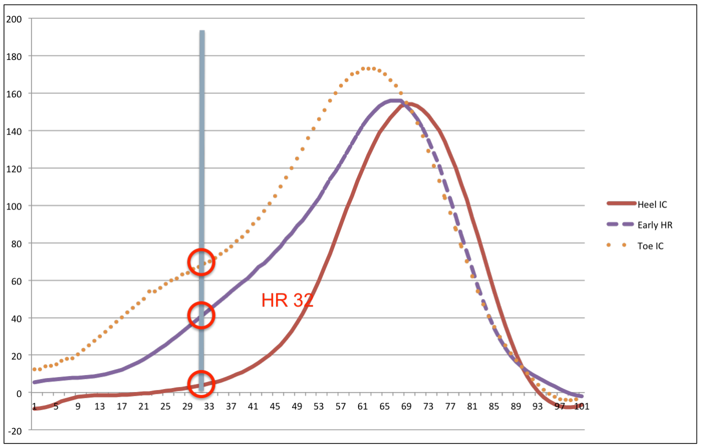

Figure 6 HR32

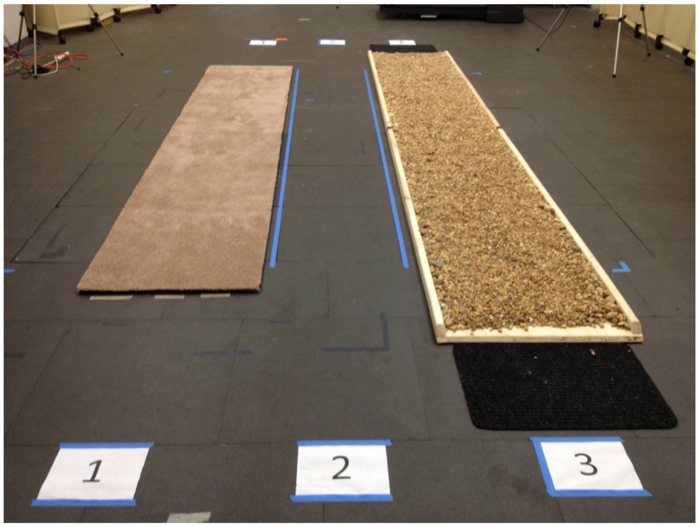

Figure 7 4-meter Walkways
1: Pile Carpet; 2: Vinyl Tile; 3: Loose Gravel.

Statistical Analysis

Five 2 X 3 factorial analyses of variance (ANOVAs) with repeated measures were used to analyze the following dependent variables: velocity, cadence, step length, step width, and HR32. The between-subject variable was group: ITW or TD. The within-subject variable was surface: 1. Pile carpet; 2. Vinyl tile; 3. Loose gravel. The mean and standard deviation of the dependent variables were calculated for each group and surface. The α-level was set as .05. When the test showed the statistical significance, the paired comparisons were performed between the conditions with Bonferroni adjustments. Finally, a test was conducted to determine any effects of gait development by dividing the participants into two groups, one younger than 7 years and the other older than age 7, and comparing between groups on each surface. All statistical procedures were performed with the SPSS system (International Business Machines Corp., New Orchard Road, Armonk, NY 10504).

Results

Thirty participants, 15 children with Idiopathic Toe Walking (ITW) and 15 typically developing (TD) children, completed the study. In children with ITW group, the average age, height, and weight were 6.8 years old (SD= 1.6), 1.22 m (SD= .11), and 27.4 kg (SD=7.9). Fifty-seven percent of the ITW participants had hardwood floors and 64% of them had carpet floors in their household. In TD children group, the average age, height, and weight were 7.8 years old (SD= 1.5), 1.30 m (SD= .12), and 29.1 kg (SD=9.0) (Table 4). Eighty percent of the TD participants had hardwood floors and 53% of them had carpet floors in their household.

Group	Gender	Age (year)	Height (cm)	Weight (kg)
TD	Female	7	118	20.7
TD	Male	9	130	26.8
TD	Male	7	125	23.1
TD	Female	8	142	36.2
TD	Male	9	127	37.8
TD	Female	5	111	17.2
TD	Female	10	145	33.4
TD	Female	9	137	24.8
TD	Male	9	143	44.6
TD	Male	8	144	45.7
TD	Female	8	130	29.2
TD	Female	7	121	22.9
TD	Female	5	106	16.8
TD	Male	9	134	31.8
TD	Male	7	127	25.2
TD MEAN		7.8 (1.5)	130 (12)	29.1 (9)
ITW	Female	4	102	16.3
ITW	Male	8	134	29.4
ITW	Male	6	114	23.1
ITW	Female	5	109	21.6
ITW	Female	10	128	25.6
ITW	Female	5	102	16.6
ITW	Male	8	127	44.8
ITW	Male	9	137	39.9
ITW	Male	7	123	34.2
ITW	Female	6	122	30.4
ITW	Male	6	120	23.4
ITW	Male	7	131	28.3
ITW	Female	7	125	25.2
ITW	Female	6	115	22.5
ITW	Male	8	132	29.5
ITW MEAN		6.8 (1.6)	122 (11)	27.4 (7.9)
OVERALL MEAN		7.3 (1.6)	126 (12)	28.5 (8.4)

Table 4 *Participant Description (TD and ITW)*

In between-subject (Group) effects, HR32 was significantly different ($P < 0.001$). Velocity ($P = 0.724$), cadence ($P = 0.099$), step length ($P = 0.081$), step width ($P = 0.693$) were not significantly different. In within-subject (Surface) effects, velocity, cadence, step length, and HR32 were significantly different among surface conditions ($P < 0.001$). Step width was not significantly different among surface conditions ($P = 0.147$) (Table 5). Group and surface had significant interaction on HR32 ($P < 0.004$).

After pairwise comparisons with Bonferroni adjustments, combining data from both groups, velocity, cadence, step length, and HR32 were significantly different among surfaces. Combining data from both groups, velocity was substantially lower on gravel than the other surfaces. Participants walked with significantly lower velocity on gravel than on both vinyl tile ($p < 0.001$) and carpet ($p < 0.001$). Between groups, there were no significant differences in velocity ($p = 0.724$). Combining data from both groups, cadence was substantially lower on gravel than the other surfaces. Participants walked with significantly higher cadence on vinyl tile than on both carpet ($p < 0.001$) and gravel ($p < 0.001$). Cadences were also significantly higher on vinyl tile than carpet ($p < 0.001$). Between groups, there were no significant differences in cadence ($p = 0.099$). Combining data from both groups, step length was substantially shorter on gravel than the other surfaces. Participants walked with significantly longer step length on carpet than on both vinyl tile ($p = 0.03$) and gravel ($p < 0.001$). Step length was also significantly longer on vinyl tile than gravel ($p < 0.001$). Between groups, there were no significant differences in step length ($p = 0.081$). Combining data from both groups, HR32 was substantially lower on gravel than the other surfaces. Participants walked with significantly lower HR32 on gravel than on both vinyl tile ($p = 0.003$) and carpet ($p < 0.001$). Between groups, there was significant difference in HR32 ($p < 0.001$) (Table 6). Independent t-tests between the age groups (<7 years vs. >7 years) revealed no significant differences based on gait development on any surface.

		Carpet	Vinyl Tile	Gravel	*P*-value		
Velocity	TD	1.11	1.15	0.74	Group	0.724	
(m/s)	ITW	1.11	1.12	0.71	Surface	<0.001	*
Cadence	TD	125	130	109	Group	0.099	
(step/min)	ITW	133	138	114	Surface	<0.001	*
Step Length	TD	0.54	0.53	0.41	Group	0.081	
(m)	ITW	0.5	0.49	0.37	Surface	<0.001	*
Step Width	TD	0.12	0.11	0.11	Group	0.693	
(m)	ITW	0.12	0.11	0.13	Surface	0.147	
HR32**	TD	20	14	12	Group	<0.001	*
(mm)	ITW	34	35	17	Surface	<0.001	*

Table 5 *Surface Effects on the Gait Pattern, TD vs. ITW* (TD n=15, ITW n=15).
* Representing statistical significance **significant interaction

	Carpet vs. Vinyl tile	Vinyl tile vs. Gravel	Carpet vs. Gravel
Velocity	0.13	<0.001*	<0.001*
Cadence	<0.001*	<0.001*	<0.001*
Step Length	0.006*	<0.001*	<0.001*
HR32	0.18	0.003*	<0.001*

Table 6 *P-value of the Pairwise Comparisons with Bonferroni Adjustments*
* Indicates statistical significant

Discussion

The study tested the effect of walking surface on the gait and heel rise timing of children with Idiopathic Toe Walking (ITW). The walking surfaces in the current study are surfaces that people commonly encounter. The effects of surface on the gait pattern are poorly understood, especially on the gait pattern of pathological gait. Comparing the gait patterns between TD children and children with ITW on different surfaces reveals whether or not different sensations caused by different walking surfaces have different effects on TD children and children with ITW. A novel measure, HR32, was tested to determine whether it could distinguish between the gait of TD children and that of children with ITW, even when the latter adopt a “normal” heelstrike.

The study was designed to assess a broad age range, but the breadth might be a limitation if differences are noted between the younger and older participants. However, no significant difference was found between groups when the participants were divided into groups younger than and older than 7 years. The current study only assessed comfortable, self-selected walking speed. Velocity was reported to have significant influence on many kinematic parameters in sagittal, frontal, and transverse planes (Schwartz, Rozumalski, & Trost, 2008). Various velocities are suggested to be tested in future studies, anticipating that speed might alter the influence of surface on gait. The force platform was not available on carpet and gravel surfaces; therefore, kinetic data were not collected in the current study. The gait exams were conducted under barefoot condition, limiting our ability to generalize results to shod walking conditions.

Both TD and ITW groups showed similar changed gait pattern, faster velocity, higher cadence, and longer step length on vinyl surface. There was no significant difference among the gait parameters between TD and ITW groups. The similar changed gait pattern may be due to the surface had similar effects in both TD and ITW groups, or the parameters we chose could not show the difference.

All children walked slowest, showed lowest cadence, and had shortest step length on gravel. This is possibly due to the feeling of unsteadiness produced by the uneven terrain. The gravel “settled” underfoot with each step, and children may have slowed to maintain balance. However, step width did not increase on gravel, and step width often increases when balance is a concern. In a multi-surface terrain study, Marigold and Patla found multi-surface terrain poses a greater challenge to balance reflected by the increased variability (2008). We found similar results of higher variability on gait parameters across the surfaces. However, compared with TD children, children with ITW had higher variability. Alternatively, the children reported that barefoot walking on the gravel was least comfortable of the three surfaces so they might have slowed their gait to minimize ground reaction forces." Walking on vinyl tile, all children also walked fastest, and showed highest cadence. This may be due to the consistency of level ground. The participants showed confidence walking on the surface. Under the circumstance, they may utilize ground reaction force as their benefit, therefore, faster speed and higher cadence found. On carpet, all children had longest step length. This may be due to the shock absorption of the carpet. Children reported that walking barefooted on carpet was the most comfortable of the three surfaces. In kinetics, although we didn't have force platforms underneath the surfaces, we assumed that surfaces had different rates of shock absorption. Therefore, the impact of the ground reaction force that participants felt on each surface may have varied. Avoiding the impact of ground reaction force can be a possible cause of the observed gait pattern changes.

Children with ITW had significantly higher HR32 than TD children. The result indicated that HR32 is a significant measure to distinguish toe-walking patterns. We suggest that HR32 can be a measure to quantify treatment effectiveness regardless different pathological gaits of ITW.

Surface had significant effects on HR32 of the groups of the participants. The higher HR32 in children with ITW compared to TD children were only found on vinyl tile and carpet. Children with ITW showed less toe-walking on the gravel surface. The result can be due to several possible causes: first, participants were not familiar with the gravel surface; therefore, there were carefully walking on the surface so had less toe-walking gait pattern. Second, the sensation provided by gravel surface might have overwhelmed sensory receptors in the foot, and the sensory processing mechanism was corrected, therefore, less toe-walking gait was observed. Under either circumstance, we suggest that gravel surface could be a therapeutic or training method to alleviate or reduce pathological gaits. For example, practicing none toe-walking gait may help them gain muscle memory to correct their pathological gait patterns. Overwhelming sensory inputs from gravel surface may have change to correct sensory processing dysfunction.

The current study suggests that gravel surface can be used as a training tool or possible treatment for children with ITW. TD children had similar values of velocity, cadence, step length, and step width on each of the surfaces. The gait parameters couldn’t be used for identifying toe-walking pattern. The value of the HR32 can not only indicates whether the individual had toe-walking pattern, but also quantify the pathological gait pattern across the severities in ITW.

References

Alvarez, C., De Vera, M., Beauchamp, R., Ward, V., & Black, A. (2007). Classification of idiopathic toe walking based on gait analysis: development and application of the ITW severity classification. *Gait Posture, 26*(3), 428-435. doi: 10.1016/j.gaitpost.2006.10.011

Eastwood, D. M., Menelaus, M. B., Dickens, D. R., Broughton, N. S., & Cole, W. G. (2000). Idiopathic toe-walking: does treatment alter the natural history? *J Pediatr Orthop B, 9*(1), 47-49.

Engelbert, R., Gorter, J. W., Uiterwaal, C., Putte, E., & Helders, P. (2011). Idiopathic toe-walking in children, adolescents and young adults: a matter of local or generalised stiffness? *BMC Musculoskelet Disord, 12*, 61. doi: 10.1186/1471-2474-12-61

Engstrom, P., & Tedroff, K. (2012). The prevalence and course of idiopathic toe-walking in 5-year-old children. [Research Support, Non-U.S. Gov't]. *Pediatrics, 130*(2), 279-284. doi: 10.1542/peds.2012-0225

Enqstrom, P., Van't Hooft, I., & Tedroff, K. (2012). Neuropsychiatric symptoms and problems among children with idiopathic toe-walking. *Journal of pediatric orthopedics, 32*(8), 5.

Fanchiang, H. D., & Geil, M. D. (2013). *Motion analysis of children with idiopathic toe walking and controls on three terrains with vibration intervention*. Paper presented at the GAIT & CLINICAL MOVEMENT ANALYSIS SOCIETY 2013 ANNUAL CONFERENCE, Cincinnati, OH.

Hemo, Y., Macdessi, S. J., Pierce, R. A., Aiona, M. D., & Sussman, M. D. (2006). Outcome of patients after Achilles tendon lengthening for treatment of idiopathic toe walking. *J Pediatr Orthop, 26*(3), 336-340. doi: 10.1097/01.bpo.0000217743.44609.44

Herrin, K., & Geil, M. D. (2013). Minimizing Orthotic Intervention in the Treatment of Idiopathic Toe Walking: A Randomized Controlled Trial. . *Gait and Posture, In Review*.

Hicks, R., Durinick, N., & Gage, J. R. (1988). Differentiation of idiopathic toe-walking and cerebral palsy. *J Pediatr Orthop, 8*(2), 160-163.

Hirsch, G., & Wagner, B. (2004). The natural history of idiopathic toe-walking: a long-term follow-up of fourteen conservatively treated children. *Acta Paediatr, 93*(2), 196-199.

Marigold, D. S., & Patla, A. E. (2008). Age-related changes in gait for multi-surface terrain. [Comparative Study Research Support, Non-U.S. Gov't]. *Gait Posture, 27*(4), 689-696. doi: 10.1016/j.gaitpost.2007.09.005

Perry, J., & Burnfield, J. M. (2010). *GAIT ANALYSIS: Normal and Pathological Function* (2nd ed.). Thorofare: SLACK Incorporated.

Schwartz, M. H., Rozumalski, A., & Trost, J. P. (2008). The effect of walking speed on the gait of typically developing children. *J Biomech, 41*(8), 1639-1650. doi: 10.1016/j.jbiomech.2008.03.015

Solan, M. C., Kohls-Gatzoulis, J., & Stephens, M. M. (2010). Idiopathic toe walking and contractures of the triceps surae. [Review]. *Foot Ankle Clin, 15*(2), 297-307. doi: 10.1016/j.fcl.2010.01.002

Stricker, S. J., & Angulo, J. C. (1998). Idiopathic toe walking: a comparison of treatment methods. [Comparative Study]. *J Pediatr Orthop, 18*(3), 289-293.

Sutherland, D. H., Olshen, R., Cooper, L., & Woo, S. L. (1980). The development of mature gait. *J Bone Joint Surg Am, 62*(3), 336-353.

Whittle, M. W. (1990). *GAIT ANALYSIS: AN INTRODUCTION* (4th ed.). Philadelphia: Heidi Harrison.

Williams, C. M., Tinley, P., & Curtin, M. (2010). Idiopathic toe walking and sensory processing dysfunction. *J Foot Ankle Res, 3*, 16. doi: 10.1186/1757-1146-3-16

Williams, C. M., Tinley, P., Curtin, M., & Nielsen, S. (2012). Vibration perception thresholds in children with idiopathic toe walking gait. [Research Support, Non-U.S. Gov't]. *J Child Neurol, 27*(8), 1017-1021. doi: 10.1177/0883073811432748

Zimbler, S. (2007). idiopathic Toe Walking: Current Evaluation and Management. *Orthopaedic Journal of Havard Medicine School*, 3.

CHAPTER 4

THE EFFECTS OF VIBRATION ON THE GAIT PATTERN OF CHILDREN WITH IDIOPATHIC TOE WALKING

Toe-walking, the absence of heel contact during the gait cycle, is a common pattern seen in children under three years old, but most toddlers outgrow the condition (Alvarez, De Vera, Beauchamp, Ward, & Black, 2007; Solan, Kohls-Gatzoulis, & Stephens, 2010; Stricker & Angulo, 1998; Sutherland, Olshen, Cooper, & Woo, 1980). However, the condition may persist in some children. Idiopathic Toe Walking (ITW) is diagnosed when individuals who are older than three years still walk on their toes with no sign of neurological, orthopedic or psychiatric diseases (Eastwood, Menelaus, Dickens, Broughton, & Cole, 2000; Engelbert, Gorter, Uiterwaal, Putte, & Helders, 2011; Hirsch & Wagner, 2004; Sutherland et al., 1980).

The incidence reports of ITW in the literature are widely varied. Zimbler stated, “The true incidence is unknown but appears to be as high as 5/500 births” (2007). Engelbert et al. found 12% prevalence of ITW among 384 children (2011); whereas, Engstrom found 4.9% total prevalence of ITW among 1436 children (2012). The varied results may be due to the personal experience of the clinician and/or the difficulty of differentiating ITW fom other toe-walking pathologies.

Prolonged toe-walking gait can cause harmful damage to patients’ health over time. In the short term, patients experience soreness and tightness of ankle plantarflexors sooner after a period of physical activity compared to typically developed individuals. In the long term, patients are more susceptible to muscle/tendon contracture (Engelbert et al., 2011). Generally, treatments for prolonged toe walking can be categorized into surgical and non-surgical. Depending on the severity of the condition, patients receive orthotic treatment, serial casting, botulinum toxin A injection, or muscle/tendon lengthening surgery (Hemo, Macdessi, Pierce, Aiona, & Sussman, 2006; Stricker & Angulo, 1998). Even though there is no consensus on which treatment is better than others, many clinicians report, at least anecdotally, that ITW is not rare in children, and it needs to be treated.

With the uncertainty concerning the effectiveness of ITW treatments, researchers have taken different approaches to understand the etiology and develop potential alternative treatments. Recently, some research has linked ITW to sensory processing dysfunction, which is diagnosed when an individual cannot integrate the information obtained from sensory systems to organize body movement (Williams, Tinley, & Curtin, 2010). A recent study discovered that children with ITW have a significant heightened vibration sensitivity (lower vibration perception threshold) compared to controls (Williams, Tinley, Curtin, & Nielsen, 2012). Another study was done on the neuropsychiatric symptoms among children with ITW indicated that children with ITW as a group have more neuropsychiatric problems compared to typically developing children (Engstrom, Van't Hooft, & Tedroff, 2012). Both studies suggest that neurological disorder can be one of the etiologies of ITW.

Studies have shown that human gait can be altered by age, disease, neuromuscular dysfunction or many other conditions (Engelbert et al., 2011; R. Hicks, Durinick, & Gage, 1988; Marigold & Patla, 2008). If sensory processing is involved in some children who toe-walk, then tactile and somatosensory alterations associated with vibration might influence gait patterns differently than they do in typically developing children. Moreover, if a particular frequency of the vibration is found that reduces or eliminates toe walking, it could be used as a novel treatment modality. Given the possible difference in vibration perception in children with ITW, and the anecdotal observations of a number of therapists, the possibility exists that children may choose to walk on their toes because they are either hyposensitive or hypersensitive. Ironically, a similar kinematic pattern could result from these two opposite sensory processing extremes. Sensory-seeking children may adopt a staccato toe-strike pattern to increase pressure on the forefoot and to increase the transmission of vibration through the body. Sensory-avoiding children may choose an equinus pattern, or an early heel rise pattern, simply to limit the area of the foot receiving tactile stimulus. Whole-body vibration has been used in older adults to improve their bone health, neuromotor function, and muscle strength in various populations (Lau, Yip, & Pang, 2012; Pang, Lau, & Yip, 2013). Although the effect of using vibration as a treatment still uncertain (Marin, Ferrero, Menendez, Martin, & Herrero, 2013). Some studies had shown that Whole-body vibration (WBV) improved the postural sway and ambulatory capacity in chronic stroke patients (Chan et al., 2012; Lee, Cho, & Lee, 2013).

In the current study, we investigated the effects of vibration on the gait pattern and vibration perception threshold (VPT) of children with ITW with typically developing (TD) children served as controls. We asked participants to walk barefooted on a vinyl tile walkway for ten times before and after standing on a WBV machine. The study examined whether or not participants show different gait pattern after the vibration. The results help us to understand the effects of vibration on the gait pattern of developing children, and whether we can use vibration as a training/therapeutic method to correct/improve the pathological walking pattern. VPT scores were also collected twice, before the first gait examination and after WBV intervention. The protocols of the VPT tests were according to Williams et al. (2012). The tests sought to not only verify William's et al.'s experiment, but also to study the effects of excessive vibration on vibration perception.

The study measured temporal and spatial parameters of gait with a focus on the timing of the heel rise event, which indicates the onset of Perry's third rocker. In our experience, the timing of the heel rise event is a valuable indicator of altered gait in children with ITW (Fanchiang & Geil, 2013). Because many children with ITW maintain adequate ankle range of motion for some time, they are capable of achieving normal standing and normal heel contact in gait. When they are observed, as in a laboratory setting, many exhibit far more heel-to-toe gait than they do in settings that are more customary to them. Despite these apparently "normal" steps, we have learned that early heel rise still occurs in most (Herrin & Geil, 2013). Consequently, this study tested the following hypotheses: 1. Participants will show different velocity, cadence, step length, and step width after the WBV intervention. 2. Children with ITW will show hypersensitivity to vibration. 2. Excessive vibration desensitized the perception to vibration.

Methods

The study was an analysis of motion data collected from children with Idiopathic Toe Walking (ITW) and typically developing (TD) children, aged from 4 to 10 years old, assessed at the Georgia State University (GSU) Biomechanics Laboratory. The participant recruitment was based on a referral system. Physical therapists provided information to children with ITW who were interested in participating. Potential TD participants were referred from elementary schools around metro Atlanta. Qualified participants were recruited for the current study. Exclusion criteria included history of neuromotor or musculoskeletal disorders, unresolved orthopedic injury, or other inability to walk through a distance of 4 m approximately 20 times. Before any participant was recruited, the protocols were approved by the GSU Institutional Review Board (IRB). Before the study started, each child's parent signed parental permission forms and participants of appropriate age signed or verbally acknowledged informed assent. The experiment took approximately 45 minutes including participant preparation, and a gait examination.

The following demographic/anthropometric data were collected for each participant: date of birth, onset of walking, family history of ITW, height, weight, knee width, ankle width, and leg length. Each participant then quietly played in the lab for 15 minutes to reduce any potential environmental impact (Williams et al., 2012). Next, we placed fifteen reflective markers over key landmarks on each participant's lower extremity (Vicon Plug-In-Gait Lower Limb Sacrum model).

Vibration Perception Threshold (VPT) was measured using VSA-3000 Vibratory Sensory Analyzer (Medoc, Israel) (Figure 8). A 12 mm diameter Teflon-coated tactor protrudes out from a hole of the footplate that allows the toe to rest on the pin. The VSA-3000 delivers the vibration through the pin, which is movable to maintain consistent pressure on the toe. The frequency of the output vibration of the VSA-3000 is 100 Hz. The range of the amplitude is from 0 to 130 μm. To measure the VPT score, the "levels with dummy options" program was chosen according to William el al. (2012). In this program, the amplitude initially increased amplitude by 0.8 μm until the participant indicated verbally that he or she felt the stimulus. After the positive indication to the stimulus, the amplitude decreased by half of the last increased amplitude. The increase and decrease of the amplitude changed each time upon negative indication of the stimulus. The dummy option in the test inserted random trials of no vibration but still required the response from the participant. During the test, the environment was kept quiet and comfortable. The vibration was first demonstrated on each participant's right index finger tip to ensure that the participant understood what the vibration feels like (Williams et al., 2012). The participant was seated in a chair with the VSA-3000 in front of the chair. Then, the participant rested his/her right hallux on the tactor of the VSA-3000 footplate and completed the test program.

Figure 8 VSA-3000 Vibratory Sensory Analyzer

Next, a gait exam was conducted. A seven-camera Vicon motion analysis system (OMG, Oxford, England) tracked the motion of fifteen reflective markers. Kinematic data were collected using Vicon Nexus software version 1.8 (OMG, Oxford, England). A static Plug-In-Gait trial was collected, and then participants walked at a comfortable self-selected speed over a level, smooth 5 m walkway. Ten trials were collected during the first gait exam for each participant.

Following the first gait analysis, a whole body vibration (WBV) intervention was conducted. Each participant stood barefoot for one minute on a WBV machine (Soloflex, Hillsboro, U.S.A.) vibrating at 30 Hz (Figure 9). To monitor each child's comfort, a Faces Pain Scale was presented during the intervention (C. L. Hicks, von Baeyer, Spafford, van Korlaar, & Goodenough, 2001). The scale uses six faces to indicate the pain level from 0 to 10 (Figure 10). Each participant pointed at a face every 20 seconds to indicate their level of discomfort. If the participant indicated a level is at 6 (the fourth face from the left) or higher, the vibration intervention stopped immediately.

Figure 9 Whole-body Vibration Machine

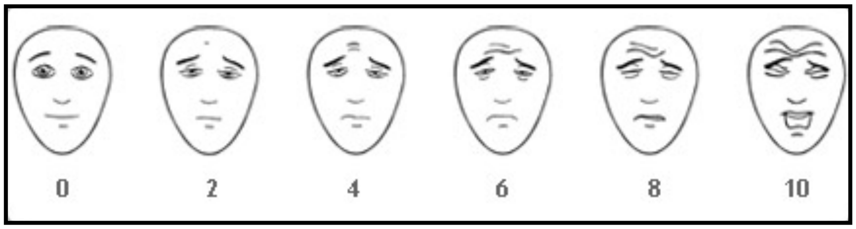

Figure 10 Faces Pain Scale

After the vibration intervention, each participant repeated the VPT test and the gait exam. The procedures of the second VPT test and the second gait exam were the same as the first ones. Ten trials for each participant were collected during the second gait exam.

Spatiotemporal parameters, i.e., velocity, cadence, step length, and step width were extracted from the kinematic data using Vicon Polygon software version 3 (OMG, Oxford, England). Besides the parameters mentioned above, in current study, we studied the timing of the heel rise. Early heel rise is an indicator of potential gait abnormities (Alvarez et al., 2007). Alvarez et al. categorized toe-walking into three severity classes: mild (presence of first rocker), moderate (presence of an early third ankle rocker), and severe (predominant early ankle moment). The classification methods have illustrated the characteristics of ITW; but to further quantify toe-walking pattern across all severity levels, a new measure is needed. A measure not only differentiates TD and ITW walking patterns, but also quantifies the severity of toe-walking.

Normal third ankle rocker occurs between heel rise (32 % of gait cycle) and toe off (60% of gait cycle) (Perry & Burnfield, 2010; Whittle, 1990). Therefore, an early third rocker is when the heel rise event happens earlier than 32% of the gait cycle. Because the heel marker is attached to participant’s heel. During mid-stance, when the foot is flat to the ground, the heel marker height stays the same; when heel rise happens, the heel marker height rises regardless the severity (Figure 11). Therefore, an increase in heel marker height above baseline at 32% of the gait cycle is an indication of early heel rise event. Furthermore, both typically developing children and children with ITW show positive slopes on their heel marker height graph between heel rise to mid-swing, due to forward and upward body movement. Therefore, the greater the heel marker height at 32% of the gait cycle suggests the earlier heel rise event occurrence. In the current study, heel rise was assessed by determining the heel marker height at 32% of the gait cycle (HR32). HR32 was measured as the difference between the heel marker z coordinate in a static flat-footed trial (Z_i) and the z coordinate at 32% of the gait cycle (Z_f) (Figure 12). The greater the Z_f results the greater HR32, which indicates an early heel rise. The Z_f and Z_i were acquired using both Vicon Polygon software and a custom Matlab (The Mathworks, Inc., Natrick, MA) program.

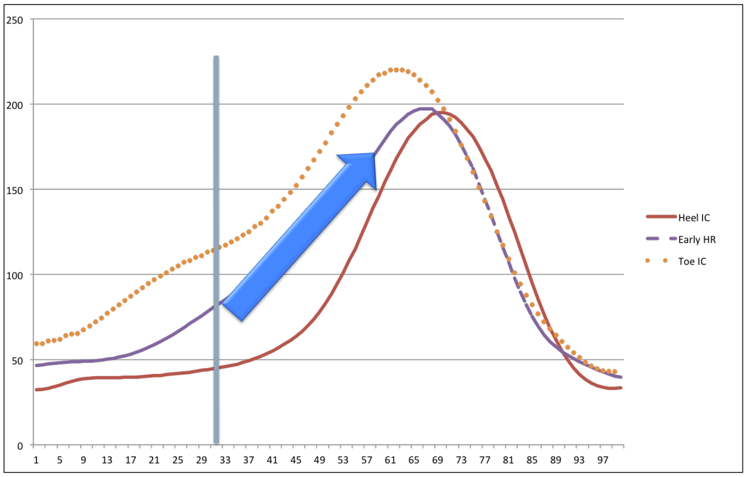

Figure 11 Heel Marker Height

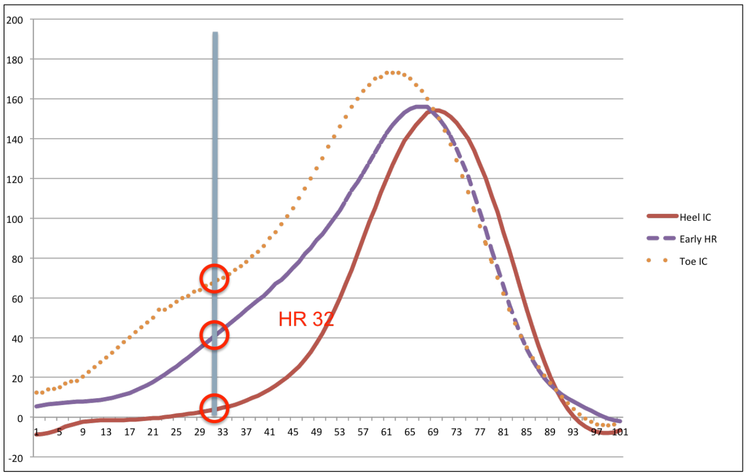

Figure 12 HR32

Statistical Analysis

Six 2 X 2 factorial analyses of variance (ANOVAs) with repeated measures were used to analyze the following dependent variables: velocity, cadence, step length, step width, HR32, and VPT. The between-subject variable was group: ITW or TD. The within-subject variable included Pre-WBV and Post-WBV. The mean and standard deviation of the dependent variables were calculated for each group and condition. The α-level was set as .05. Finally, a test was conducted to determine any effects of gait development by dividing the participants into two groups, one younger than 7 years and the other older than age 7, and comparing between groups on each surface. All statistical procedures were performed with the SPSS system (International Business Machines Corp., New Orchard Road, Armonk, NY 10504).

Results

Thirty participants, 15 children with Idiopathic Toe Walking (ITW) and 15 typically developing (TD) children, completed the study. In children with ITW group, the average age, height, and weight were 6.8 years old (SD= 1.6), 1.22 m (SD= .11), and 27.4 kg (SD=7.9). Fifty-seven percent of the ITW participants had hardwood floors and 64% of them had carpet floors in their household. In TD children group, the average age, height, and weight were 7.8 years old (SD= 1.5), 1.30 m (SD= .12), and 29.1 kg (SD=9.0) (Table 7). Eighty percent of the TD participants had hardwood floors and 53% of them had carpet floors in their household.

Group	Gender	Age (year)	Height (cm)	Weight (kg)
TD	Female	7	118	20.7
TD	Male	9	130	26.8
TD	Male	7	125	23.1
TD	Female	8	142	36.2
TD	Male	9	127	37.8
TD	Female	5	111	17.2
TD	Female	10	145	33.4
TD	Female	9	137	24.8
TD	Male	9	143	44.6
TD	Male	8	144	45.7
TD	Female	8	130	29.2
TD	Female	7	121	22.9
TD	Female	5	106	16.8
TD	Male	9	134	31.8
TD	Male	7	127	25.2
TD MEAN		7.8 (1.5)	130 (12)	29.1 (9)
ITW	Female	4	102	16.3
ITW	Male	8	134	29.4
ITW	Male	6	114	23.1
ITW	Female	5	109	21.6
ITW	Female	10	128	25.6
ITW	Female	5	102	16.6
ITW	Male	8	127	44.8
ITW	Male	9	137	39.9
ITW	Male	7	123	34.2
ITW	Female	6	122	30.4
ITW	Male	6	120	23.4
ITW	Male	7	131	28.3
ITW	Female	7	125	25.2
ITW	Female	6	115	22.5
ITW	Male	8	132	29.5
ITW MEAN		6.8 (1.6)	122 (11)	27.4 (7.9)
OVERALL MEAN		7.3 (1.6)	126 (12)	28.5 (8.4)

Table 7 *Participant Description*

No child indicated discomfort with the study or the WBV intervention, and all WBV sessions were continued to completion. Velocity, cadence, step length, step width, and VPT scores were not significantly different between TD and ITW groups combining before and after WBV trials. However, HR32 was significantly different between TD and ITW groups combining before and after WBV trials (*P* < .001) (Table 8). None of the primary kinematic measures (velocity, cadence, step length, step width, and HR32) was significantly different following the WBV intervention (Table 8). Vibration perception threshold was significantly changed following the WBV intervention in both groups (*P* < .001). The effect of WBV was quite similar in both groups, with the average threshold for typically developing children increasing from 0.58 µm to 1 µm, while the threshold for children with ITW increasing from 0.58 µm to 1.05 µm. Independent t-tests between the age groups (<7 years vs. >7 years) revealed no significant differences based on gait development on any surface.

		Pre-vibration		**Post-vibration**		***P*-value**		
		Mean	SD	Mean	SD			
Velocity (m/s)	TD	1.15	(0.12)	1.13	(0.13)	Group	0.445	
	ITW	1.12	(0.17)	1.11	(0.19)	Vibration	0.649	
Cadence (step/min)	TD	130	(15)	129	(13)	Group	0.122	
	ITW	138	(12)	134	(9)	Vibration	0.076	
Step length (m)	TD	0.53	(0.04)	0.53	(0.05)	Group	0.076	
	ITW	0.49	(0.07)	0.49	(0.08)	Vibration	0.754	
Step width (m)	TD	0.11	(0.03)	0.12	(0.03)	Group	0.496	
	ITW	0.11	(0.04)	0.10	(0.03)	Vibration	0.315	
HR32 (mm)	TD	14	(12)	14	(13)	Group	<0.001	*
	ITW	33	(11)	34	(15)	Vibration	0.791	
VPT Score (µm)	TD	0.58	(0.43)	1.02	(0.78)	Group	0.921	
	ITW	0.58	(0.25)	1.05	(0.48)	Vibration	<0.001	*

Table 8 *Vibration Effects on the Gait Pattern and VPT, TD vs. ITW*
(TD n=15, ITW n=15). * Representing statistical significance

Discussion

The study tested the effect of whole-body vibration (WBV) on the gait of children with Idiopathic Toe Walking (ITW) and on their perception of vibration. Comparing the gait patterns between typically developing (TD) children and children with ITW walking on the walkway after WBV helped us understand whether vibration had different effects on TD children and children with ITW. The VPT tests conducted before and after WBV showed whether vibration immediately changed vibration sensitivity of the participants. A novel measure, HR32, was tested whether it could identify ITW walking patterns.

There were several limitations associated with the current study. The study was designed to assess a broad age range, but the breadth might be a limitation if differences are noted between the younger and older participants. However, no significant difference was found between groups when the participants were divided into groups younger than and older than 7 years. We tested only one walking condition: barefoot walking over smooth, level ground at a comfortable, self-selected speed. This minimized variability but also limits the ability to generalize the results to other conditions. The current study only assessed comfortable, self-selected walking speed. Velocity was reported to have significant influence on many kinematic parameters in sagittal, frontal, and transverse planes (Schwartz, Rozumalski, & Trost, 2008). Various velocities are suggested to be tested in future studies, anticipating that speed might alter the influence of surface on gait. The force platform was not available; therefore, kinetic data were not collected in the current study. The gait exams were conducted under barefoot condition, limiting our ability to generalize results to shod walking conditions. Whole Body Vibration is not commonly used in this population, and is clinically more often associated with use in therapy for stroke patients (Chan et al., 2012; Lee et al., 2013). Therefore, we had no precedent or guidelines regarding amplitude, frequency, and duration of the WBV intervention.

Despite the result that whole-body vibration did not have significant within-subject or between-subject effects on velocity, cadence, step length, and step width, we found a significant between-subject effect on HR32. This result confirms that HR32 is a useful measure of the ITW walking pattern. The lack of statistically significant differences does not completely exclude the possibility of whole-body vibration as a treatment method for toe-walking. Different frequency, magnitude, duration need to be tested to exclude the effects of whole-body vibration. Vibration with longer durations and at higher frequencies is recommended for future studies. In Holmes et al.'s study, the vibration frequency that most likely to trigger muscle spindle was indicated as 80Hz (2012). The other possible cause of no difference on the gait pattern can be due to the half-life of the effect of whole-body vibration. Clinicians who use WBV therapeutically have noted that the effects wear off more rapidly than other modalities. Before the second gait exam, each participant had the second VPT test, which took about five minutes to complete. The vibration effects on the gait pattern may not continue throughout the second gait exam.

The VPT was not significantly different between TD children and children with ITW. This result was in conflict with the result from William et al.'s study. In William et al.'s study, they found VPT scores were significantly different between TD and ITW groups. They stated that children with ITW had hypersensitivity to vibration, therefore, the etiology of ITW may relate to sensory processing dysfunction. To verify this important result, we used an identical machine, selected the same testing program, and ran the same procedures. Not being able to repeat results found in William et al.'s study was unexpected. Moreover, the averaged VPT scores of TD children and children with ITW from William et al.'s study were 1.8 μm and 1.0 μm, respectively ($P = 0.001$), while our results from before the WBV intervention were 0.58 μm and 0.55 μm for TD and ITW groups, respectively ($P = 0.852$). One possible explanation for this conflict was a discrepancy between the vibration output of the two machines or the pressure provided on the tactor. Another possibility rests in the lack of homogeneity among children with ITW. Clinicians note that some present with toe walking secondary to hyposensitivity, others hypersensitivity, and still others low muscle tone. Two random samples of toe walkers could therefore be dominated by two different etiologies, producing different VPT results. Tests with larger sample sizes should be considered, along with other means to independently identify the potential etiology.

In within-subject effect, after WBV vibration, we found significantly elevated VPT scores after standing on a WBV platform for 60 seconds. Excessive vibration intervention immediately reduced the sensitivity to the vibration. Excessive vibration may temporally overwhelm the sensory receptors, so the receptors did not respond to the weaker vibration. The result indicates that vibration intervention can be used to temporally reduce vibration sensitivity for therapeutic or treatment purposes. The current study used 30Hz vibration for 60 seconds. The effects of other frequency, amplitude, and duration of the vibration are still not clear. However, vibration is certainly worth considering as a potential therapeutic or treatment method to children with ITW.

References

Alvarez, C., De Vera, M., Beauchamp, R., Ward, V., & Black, A. (2007). Classification of idiopathic toe walking based on gait analysis: development and application of the ITW severity classification. *Gait Posture, 26*(3), 428-435. doi: 10.1016/j.gaitpost.2006.10.011

Chan, K. S., Liu, C. W., Chen, T. W., Weng, M. C., Huang, M. H., & Chen, C. H. (2012). Effects of a single session of whole body vibration on ankle plantarflexion spasticity and gait performance in patients with chronic stroke: a randomized controlled trial. *Clin Rehabil, 26*(12), 1087-1095. doi: 10.1177/0269215512446314

Eastwood, D. M., Menelaus, M. B., Dickens, D. R., Broughton, N. S., & Cole, W. G. (2000). Idiopathic toe-walking: does treatment alter the natural history? *J Pediatr Orthop B, 9*(1), 47-49.

Engelbert, R., Gorter, J. W., Uiterwaal, C., Putte, E., & Helders, P. (2011). Idiopathic toe-walking in children, adolescents and young adults: a matter of local or generalised stiffness? *BMC Musculoskelet Disord, 12*, 61. doi: 10.1186/1471-2474-12-61

Engstrom, P., & Tedroff, K. (2012). The prevalence and course of idiopathic toe-walking in 5-year-old children. [Research Support, Non-U.S. Gov't]. *Pediatrics, 130*(2), 279-284. doi: 10.1542/peds.2012-0225

Engstrom, P., Van't Hooft, I., & Tedroff, K. (2012). Neuropsychiatric symptoms and problems among children with idiopathic toe-walking. [Research Support, Non-U.S. Gov't]. *J Pediatr Orthop, 32*(8), 848-852. doi: 10.1097/BPO.0b013e31826bec08

Fanchiang, H. D., & Geil, M. D. (2013). *Motion analysis of children with idiopathic toe walking and controls on three terrains with vibration intervention*. Paper presented at the GAIT & CLINICAL MOVEMENT ANALYSIS SOCIETY 2013 ANNUAL CONFERENCE, Cincinnati, OH.

Hemo, Y., Macdessi, S. J., Pierce, R. A., Aiona, M. D., & Sussman, M. D. (2006). Outcome of patients after Achilles tendon lengthening for treatment of idiopathic toe walking. *J Pediatr Orthop, 26*(3), 336-340. doi: 10.1097/01.bpo.0000217743.44609.44

Herrin, K., & Geil, M. D. (2013). Minimizing Orthotic Intervention in the Treatment of Idiopathic Toe Walking: A Randomized Controlled Trial. . *Gait and Posture, In Review*.

Hicks, C. L., von Baeyer, C. L., Spafford, P. A., van Korlaar, I., & Goodenough, B. (2001). The Faces Pain Scale-Revised: toward a common metric in pediatric pain measurement. *Pain, 93*(2), 173-183.

Hicks, R., Durinick, N., & Gage, J. R. (1988). Differentiation of idiopathic toe-walking and cerebral palsy. *J Pediatr Orthop, 8*(2), 160-163.

Hirsch, G., & Wagner, B. (2004). The natural history of idiopathic toe-walking: a long-term follow-up of fourteen conservatively treated children. *Acta Paediatr, 93*(2), 196-199.

Holmes, T. C., Floyd, L. M., & Dean, J. C. (2012). *Vibration impairsproprioception during active cyclical ankle movements*. Paper presented at the American Society of Biomechanics, Gainsville, FL.

Lau, R. W., Yip, S. P., & Pang, M. Y. (2012). Whole-body vibration has no effect on neuromotor function and falls in chronic stroke. *Med Sci Sports Exerc, 44*(8), 1409-1418. doi: 10.1249/MSS.0b013e31824e4f8c

Lee, S. W., Cho, K. H., & Lee, W. H. (2013). Effect of a local vibration stimulus training programme on postural sway and gait in chronic stroke patients: a randomized controlled trial. *Clin Rehabil, 27*(10), 921-931. doi: 10.1177/0269215513485100

Marigold, D. S., & Patla, A. E. (2008). Age-related changes in gait for multi-surface terrain. [Comparative Study Research Support, Non-U.S. Gov't]. *Gait Posture, 27*(4), 689-696. doi: 10.1016/j.gaitpost.2007.09.005

Marin, P. J., Ferrero, C. M., Menendez, H., Martin, J., & Herrero, A. J. (2013). Effects of whole-body vibration on muscle architecture, muscle strength, and balance in stroke patients: a randomized controlled trial. *Am J Phys Med Rehabil, 92*(10), 881-888. doi: 10.1097/PHM.0b013e318292336c

Pang, M. C., Lau, R. K., & Yip, S. P. (2013). The effects of whole-body vibration therapy on bone turnover, muscle strength, motor function, and spasticity in chronic stroke: a randomized controlled trial. *Eur J Phys Rehabil Med, 49*(4), 439-450.

Perry, J., & Burnfield, J. M. (2010). *GAIT ANALYSIS: Normal and Pathological Function* (2nd ed.). Thorofare: SLACK Incorporated.

Schwartz, M. H., Rozumalski, A., & Trost, J. P. (2008). The effect of walking speed on the gait of typically developing children. *J Biomech, 41*(8), 1639-1650. doi: 10.1016/j.jbiomech.2008.03.015

Solan, M. C., Kohls-Gatzoulis, J., & Stephens, M. M. (2010). Idiopathic toe walking and contractures of the triceps surae. [Review]. *Foot Ankle Clin, 15*(2), 297-307. doi: 10.1016/j.fcl.2010.01.002

Stricker, S. J., & Angulo, J. C. (1998). Idiopathic toe walking: a comparison of treatment methods. [Comparative Study]. *J Pediatr Orthop, 18*(3), 289-293.

Sutherland, D. H., Olshen, R., Cooper, L., & Woo, S. L. (1980). The development of mature gait. *J Bone Joint Surg Am, 62*(3), 336-353.

Whittle, M. W. (1990). *GAIT ANALYSIS: AN INTRODUCTION* (4th ed.). Philadelphia: Heidi Harrison.

Williams, C. M., Tinley, P., & Curtin, M. (2010). Idiopathic toe walking and sensory processing dysfunction. *J Foot Ankle Res, 3*, 16. doi: 10.1186/1757-1146-3-16

Williams, C. M., Tinley, P., Curtin, M., & Nielsen, S. (2012). Vibration perception thresholds in children with idiopathic toe walking gait. [Research Support, Non-U.S. Gov't]. *J Child Neurol, 27*(8), 1017-1021. doi: 10.1177/0883073811432748

Zimbler, S. (2007). idiopathic Toe Walking: Current Evaluation and Management. *Orthopaedic Journal of Havard Medicine School*, 3.