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by

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THESIS

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ABSTRACT

Treadmill (TM) walking may be a way to combat obesity and socio-behavioral barriers associated with children with Autism Spectrum disorder (ASD), though tripping-risk has not yet been assessed for this population through use of spatial-temporal gait analysis. The aim of this project/study was to examine spatial-temporal walking mechanics and lower extremity tripping descriptors between over ground (OG) and TM gait conditions in children with ASD compared to children with neurotypical development (NT). Kinematics data were obtained through tridimensional motion analysis where participants, 10 children with ASD and 9 age- and sex-matched NT controls, were outfitted with retroreflective markers on their lower extremities. Participants were instructed to walk OG over a 10-meter walkway at a self-selected pace for 12 trials, then walked on a TM at a self-selected pace for 5-minutes continuously. Variables of interest were evaluated through independent samples *t*-tests and paired samples *t*-tests to identify significant difference between groups, conditions, and limbs (α=0.05). Statistical analysis revealed groups had similar responses during the TM condition such as increased time in double limb support, decreased gait velocity, increased step width, and an increased toe clearance. However, only the ASD group displayed decreased step lengths indicating shorter steps were taken during the TM condition. Additionally, the ASD group portrayed limb differences for TC and SL. Findings suggest TM walking may not increase tripping risk in children with ASD, but rather, may elicit safer gait strategies, consistent with previous findings. TM walking implemented as a future intervention, may result in reduced obesity rates, and future researchers may investigate energy expenditure knowing that children with ASD may not experience a trip or fall despite previously associated motor deficits.

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CHAPTER 1. INTRODUCTION

Autism Spectrum Disorder (ASD) is neurobehavioral disorder characterized by delayed and impaired social interaction, language, and social communication with stereotyped repetitive patterns of behavior or interests (American Psychiatric Association, 2013). The prevalence of ASD has increased from 1 in 69 children in 2012 to 1 in 59 children in 2019 (CDC, 2019; Baio, 2018). This increase may be due to increased awareness in ASD or changes in diagnostic criteria (Matson & Kozlowski, 2011). ASD can be diagnosed through various tools that observe social-behavioral and communication characteristics of individuals, however, motor assessments have not been implemented into diagnostic criteria although motor anomalies were observed in the ASD population by Kanner (1943) more than half a century ago.

Motor impairments have been identified as associative symptoms in individuals with ASD (Ming et al., 2007) supported by pathological studies which reported abnormalities in the cerebellum and subcortical white matter; the regions that mediate motor function (Bauman & Kemper, 2005; Courchesne, 2002). Early studies have suggested that ASD may be caused by a disruption within the basal ganglia fronto-striatal region as motor abnormalities had been considered "Parkinsonian-like" such as abnormal posture and gait (Damasio & Maurer, 1978; Maurer & Damasio, 1982). However, recent studies allowed for further input into the subject and suggested that individuals with ASD had difficulty with motor preparation, which further supports previous findings of fronto-striatal dysfunction (Rinehart et al., 2001). Thus, it has been proposed that individuals with ASD may exhibit dysfunctional motor characteristics such as deficits in motor milestone development (Provost et al., 2007; Teitelbaum et al., 1998), impaired postural control (Kohen-Raz et al., 1992; Minshew et al., 2004; Vernazza-Martin et al., 2005), lack of motor coordination (Miyahara et al., 1997), clumsiness (Ghaziuddin & Butler, 1998), and deficits in fine and gross motor movements (Noterdaeme et al., 2002). Overall, multiple studies support the idea that motor deficits are a root symptom of the disorder (Bo et al., 2016; Ming et al., 2007; Noterdaeme et al., 2002).

Contemporary studies suggest that motor-focused research, rather than psychiatric-focused research, may have more potential to assist in explaining the neurobiological basis of ASD, and may also lead to improved diagnostic outcomes (Minshew et al., 2004; Rinehart et al., 2006). Previous research has examined over-ground (OG) gait function in children with ASD and revealed results such as reduced stride length, reduced ground reaction forces (Ambrosini et al., 1998), reduced stride length, reduced ankle dorsiflexion and knee extension, increased hip flexion at toe-off (Vilensky et al., 1981), increased cadence, reduced peak ankle and hip flexion (Calhoun et al., 2011), reduced stride length and increased stance time (Weiss et al., 2013), and increased variability in stride length (Rinehart et al., 2006). Contemporary findings have revealed children with ASD display an increased stride width variability, decreased magnitude of variability in terminal swing, movement variability, altered patterns to healthy controls, widened base of support, and reduced range of motion (Kindregan et al., 2015) compared to neurotypically developing (NT) controls. Additional findings suggest ASD gait can be considered heterogenous (Dufek, Harry, Eggleston, & Hickman, 2018) indicating that each child has a unique gait pattern. As such, individualized asymmetry responses were observed in angular joint (hip, knee, and ankle) positions during loaded and unloaded conditions (Eggleston et al., 2018), and ground reaction forces (Eggleston et al., 2017). Additionally, children with ASD exhibited lesser lower extremity variability in terminal swing, greater stride width variability compared to children with NT, and the emerging patterns previously identified suggest that variability may be a movement descriptor in children with ASD (Eggleston et al., 2019).

Treadmill (TM) gait has been used as a method to analyze spatial-temporal parameters and lower extremity joint kinematics to compare findings to OG waking (Alton et al., 1998). Statistically significant differences have been observed between OG and TM gait in healthy adults and it was suggested that this type of research continue into special populations to contribute to clinical gait analyses research (Alton et al., 1998). Previous studies suggested that the prevalence of obesity among children with ASD may be higher than the general population of children (Curtin et al., 2005; Zuckerman et al., 2014). This could be due to the participation and inclusion deficits in physical activities this population may experience. Barriers are more prevalent in children with disabilities and may include limited access to structured and unstructured exercise, quality and location of resources for exercise, and lack of opportunities for sports in/out of school (Must et al., 2015). As a result, it was determined children with ASD were 41% less likely to participate in activities compared to their NT counterparts (Blanchard et al., 2006). Since many barriers to physical activity exists for children with ASD, utilizing TM-walking may be a mechanism to increase physical activity. However, it is not yet known how children with ASD will respond to walking on a TM.

Currently, there is a paucity of studies examining gait function in children with ASD comparing OG performance to TM-based performance. Analyzing TM-based gait in this population may add more insight into the motor characteristics associated with ASD as well as determine the safety of TM-use in this population in the hopes that future research investigate energy expenditure and physical activity/social barriers. Thus, purpose of the current study was to examine spatial-temporal walking mechanics and lower extremity tripping descriptors between OG and TM gait conditions in children with ASD compared to children with NT. It was hypothesized that there will be differences in tripping descriptors between OG and TM walking conditions in the ASD population compared to NT controls. It was also hypothesized that tripping descriptors will be different between limbs between participants with ASD and NT.

CHAPTER 2. LITERATURE REVIEW

To date, no study has compared over ground gait performance to treadmill-based performance in children with ASD. Specifically, studies have not examined tripping descriptors with spatial-temporal parameters in this population. Analyzing these parameters may add more insight into the motor characteristics associated with ASD as well as determine if treadmill gait is safe and feasible for gait analyses. Thus, the purpose of this study was to examine spatial-temporal walking mechanics and lower extremity tripping descriptors between OG and TM gait conditions in children with ASD compared to children with NT.

AUTISM SPECTRUM DISORDER DIAGNOSIS

Many assessment tools exist to diagnose social and communicative behavior and have shown good reliability, such as the Childhood Autism Rating Scale (CARS) (Schloper et al., 1986), the Behavioral Observation Scale for Autism (BOS) (Freeman et al., 1984), the Behavior Rating Instrument for Autistic and Atypical Children (BRIAAC) (Ruttenberg et al., 1977), the Autism Behavior Checklist (ABC) which is part of the Autistic Screening Instrument for Educational Planning (ASIEP) (Krug et al., 1980), the Autism Diagnostic Interview-Revised (ADI-R) (Rutter et al., 2003) and the Autism Observation Scale (Siegel et al., 1986). However, the aforementioned tools have shown issues in validity (Lord et al., 1989), specifically in discriminating higher functioning individuals with ASD compared to autistic children who are severely mentally handicapped (Krug et al., 1980). The Autism Diagnostic Observation Schedule (ADOS) differs from other assessment tools by facilitating observations of individuals suspected of having ASD on a social interaction, communication, and behavioral level (Lord et al., 1989, 2000). The ADOS provides ratings on the quality of an individual’s social behavior, rather than the absence of it and provides standardized social contexts through the examiners behavior and the materials cognitive tasks (Lord et al., 1989). The ADOS allows for the natural interaction between examiner and individual with a standardized context that provides background for all observations and the behavior of the examiner; rather than being fixated on the individual's behaviors, autistic-type movements, behavior difficulties, and sensory interests like the other assessment tools (Krug et al., 1980; Lord et al., 1989; Siegel et al., 1986).

Naturalistic social and communicative behaviors are obtained from the individual and are coded through the fifth edition of the *Diagnostic and Statistical Manual of Mental Disorders* (DSM-5; American Psychiatric Association, 2013) based algorithm through areas of social communication, social relatedness, play and imagination, and restricted and/or repetitive behaviors (Klin et al., 2007). The ADOS is considered the "gold standard" for ASD diagnoses and is used for candidates older than two years and has four modules that take 35 to 40 minutes each to administer where items are scored on a four-point scale. Module 1 is used for children who do not consistently use phrase speech, Module 2 is used for those who use phrase speech but are not verbally fluent, Module 3 is for fluent children, and Module 4 is with fluent adolescents as well as adults (Rutter et al., 2003). For individuals to receive an ADOS classification of ASD, the individual's scores must meet separate cut-off scores. A cut-off for "Autism" and a lower cut-off for "Autism Spectrum" exist where scores above the cut-offs suggest the presence of the disorder; communication domain (Module 1: Spectrum: 2; Autism: 4; Module 2: Spectrum: 3; Autism: 5; Module 3: Spectrum:2, ASD:3), social domain (Module 1: Spectrum: 4; Autism: 7; Module 2: Spectrum: 4; ASD: 6; Module 3: Spectrum: 4; Autism: 6), and a summation of the two (Module 1: Spectrum:7; Autism: 12; Module 2: Spectrum: 8; Autism: 12; Module 3: Spectrum: 7; Autism: 10) (Gotham et al., 2006; Moss et al., 2012). The behaviors of the test subjects are based on a score between zero and three; a three indicates abnormal function, a zero indicates normal behavior and the sum of the behavior scores is the overall score on the test module (Rutter et al., 2003). Overall, the ADOS provides a cost effective means of classifying a wide range of children and adults that is unaffected by language (Rutter et al., 2003). Early diagnosis of ASD leads to improved prognosis, which leads to subsequent implementation of early intervention through evidence-based interventions, and long-term increased quality of life (Elder et al., 2017).

NEUROTYPICAL DEFINED

Neurotypical (NT) or neurologically typical, is a term originally created in the late 1990's by the Asperger community to describe those who are not on the autistic spectrum, or are unaffected by a developmental disorder (Attwood, 2006). NT individuals are often described to have characteristics of typical neurological development such as lack of sensory sensitivities, ability to adapt to change, no issue interacting with peers, and no noticeable speech delays as children (*Neurotypical*, 2017). Interestingly, the term NT is used to juxtapose those with ASD in literature that compares the two populations. A rising topic in contemporary literature is examining biomechanical differences that may or may not exist between the NT population and clinical populations, such as gait analysis.

GAIT CHARACTERISTICS

Gait analysis is an advantageous means to observe how individuals develop gait from early stages of life (Berger et al., 1984, 1987; Sutherland et al., 1988), and gait disorders such as Parkinson's Disease (PD) (Dietz et al., 1995; Vieregge et al., 1997). Clinical gait analysis is also important as observable deviations from ‘normal’ patterns may aid in understanding the cause of possible gait abnormalities on case-by-case circumstances (Davis, 1997). Recently, literature regarding movement abilities in children with ASD has grown as motor impairments have been categorized as a cardinal symptom of the disorder (Fournier et al., 2010; Moran et al., 2013). Previous gait research revealed results, such as a widened base of support (Shetreat-Klein et al., 2014), reduced stride length, reduced ground reaction forces (Ambrosini et al., 1998), reduced stride length, reduced ground reaction forces reduced stride length, reduced ankle dorsiflexion and knee extension, increased hip flexion at toe-off (Vilensky et al., 1981), increased cadence, reduced peak ankle and hip flexion (Calhoun et al., 2011), reduced stride length and increased stance time (Weiss et al., 2013), and increased variability in stride length (Rinehart et al., 2006). More recent gait commonalities were recognized such as children with ASD displayed an increased stride width variability, decreased magnitude of variability in terminal swing, movement variability, altered patterns to healthy controls, widened base of support, and reduced range of motion (Kindregan et al., 2015) compared to NT controls. Individualized asymmetries were also observed in children with ASD in hip, knee, and ankle joint positions in loaded and unloaded conditions (Eggleston et al., 2018). Lower extremity joint position and ground reaction force asymmetries were also observed to be unique to each individual in a separate study (Eggleston et al., 2017). Additionally, children with ASD exhibited lesser lower extremity variability in terminal swing, and greater stride width variability compared to children with NT (Eggleston et al., 2019). The current emerging patterns previously identified suggest that variability may be a movement characteristic in children with ASD where traditional gait-related variables can be considered “heterogenous” (Dufek et al., 2018; Eggleston et al., 2019). With the heterogeneity that occurs among individuals with ASD, it is imperative that the quality of motor movements as well as the development within this population be observed on an individual level and consider gait analysis a supplement to current socio-behavioral diagnostic assessments.

TREADMILL-BASED GAIT VS. OG GAIT IN HEALTHY POPULATION

Treadmill (TM) training has been used in rehabilitation for individuals who require treatment for gait impairments that may or may not be associated with neurological disorders such as a spinal cord injury (Mehrholz et al., 2017) or a stroke (Hesse et al., 1994; Vistamehr et al., 2019). It has been previously observed that TM training is advantageous compared to over-ground (OG) gait because training can be done in a smaller space, gait speed can be better controlled, and a larger volume of steps can be collected in a shorter time (Lee & Hidler, 2008). Though some limitations of TM walking exist. In 1980, van Ingen Schenau stated that OG and TM walking are the same in reference to fundamental biomechanics (Van Ingen Schenau, 1980), however, differences in biomechanical, electromyography, and metabolic parameters observed since, have been a topic of controversy. Specifically, it has been observed that individuals walk with a higher cadence, shorter stance time, and reduced preferred walking speed on a TM compared to OG walking (Gates et al., 2012; Lee & Hidler, 2008; Row Lazzarini & Kataras, 2016; Warabi et al., 2005; Watt et al., 2010; Yang & King, 2016). Previous studies have also examined joint kinematics and temporal gait parameters between TM and OG gait (Alton et al., 1998; Murray et al., 1985; Nymark et al., 2005; Riley et al., 2007) but findings suggested inconsistencies possibly due to unmatched gait speeds in both conditions as theorized by Lee and Hidler (2008). For instance Riley et al., (2007) found that kinematics of TM and OG gait were very similar, yet another study revealed that during TM gait, individuals presented with shorter step length, and a quicker cadence in TM versus OG gait (Murray et al., 1985).

Collectively, it has been observed that overall kinematic patterns during OG gait may be similar enough to TM gait that training individuals with motor disorders on TMs may provide favorable outcomes. For example, it has been suggested that TM gait artificially reduced the an individual's natural variability, thus, creating a stable and possible more predictable gait pattern (Warabi et al., 2005), which may be beneficial when examining clinical populations. It was also observed that TM-based walking elicited gait deviations that were more distinct, thus, suggesting TM gait analysis an ideal method to detect motor control deficits (Kautz et al., 2011; van der Krogt et al., 2014).Regardless, more data is needed in different populations to understand any differences between TM and OG gait. Specifically, gaining further understanding of how healthy population differs or adapts during TM may provide insight in developing gait protocols for rehabilitation in clinical populations (Hollman et al., 2016; Lee & Hidler, 2008). Comparisons of OG and TM gait protocols are limited in the neurologically impaired, such as children with ASD, to determine if TM-based interventions are proper and safe in order to decrease barriers to physical activity they may experience.

SOCIAL AND PHYSICAL ACTIVITY BARRIERS – A CALL FOR INTERVENTION

Among children with ASD and other developmental disabilities, barriers that prevent access to physical activity are more common compared to NT peers (Must et al., 2015). The social model of disability indicates that low levels of physical activity in the ASD population may be due to society's failure to accommodate individuals with services that meet the individual's needs (Oliver, 1995). This then leads to society essentially placing children with ASD at a societal disadvantage rather than a physical disadvantage that may inhibit their access to physical activity opportunities in the community or schools (Llewellyn & Hogan, 2000). This societal disadvantage may be linked to findings that indicate children with ASD were less likely to participate in extracurricular activities that require physical activity. According to the National Survey of Children's Health, children with ASD were 41% less likely to participate in physical activities compared to children with NT at 27% (Blanchard et al., 2006). Previously, it was suggested possible social and behavioral deficits associated with the disorder may limit the opportunity to participate in physical activity (Pan, 2009). Additionally, motor impairments observed in children with ASD may also be a factor that physically prevents participation from daily, physical, or leisure activities such as sports (Gowen et al., 2008). Although children with NT are more likely to participate in such activities, children with ASD are more likely to spend more time in passive play or indulge in maladaptive behaviors making them less likely to be open to spontaneous participation (Anderson et al., 2004). Alarmingly, children with ASD may experience lack of positive experiences with exercise, feelings of failure associated with inadequacy, emotional impairments, or low self-esteem in general (Memari et al., 2015). It is with these factors that increase instances of inactivity and sedentarism in children with ASD.

An increased sedentary lifestyle may be linked to higher rates of obesity among children with ASD as they are 30% more likely to be obsess compared to the 24% experienced by children with NT (Curtin et al., 2010). Additionally, obesity may be linked to weight gain due to psychopharmacological treatments, (Must & Strauss, 1999); Maayan & Correll, 2011) and food selectivity (Curtin, Jojic, & Bandini, 2014). This behavior, otherwise known as, "picky eating", may refer to frequent food rejections related to aversions to certain textures, smells, or colors (Shedlock et al., 2016), and preference of certain food categories, like carbohydrates (Cermak, Curtin, & Bandini, 2010). Obesity or excess weight in this population is now considered a secondary condition that the ASD population may be associated with. Consequently, increased weight, leads to increased risk of chronic diseases such as diabetes, and cardiovascular disease (Must & Strauss, 1999; Casavalle et al., 2014). The rapid upsurge of ASD prevalence, and the multisystem physical, psychosocial, and systemic impairments that may be linked to higher obesity rates (Bandini et al., 2005; Rimmer et al., 2010), has emphasized the need for intervention to increase physical activity.

TREADMILL FINDINGS IN ASD POPULATION

A possible solution to increase physical activity in the ASD population is TM-based gait as previous findings suggested metabolic requirements were 23% higher during TM-based walking than OG walking in healthy adults (Parvataneni, Ploeg, Olney, & Brouwer, 2009). A recent systemic review of exercise interventions for the ASD population examined 18 studies; where only 4 focused on improvements in physical fitness and the remaining studies examined improvements in academic performance, stereotypical behaviors, cognitive skills, or behavioral skills (Lang et al., 2010). The outcomes of the 4 studies revealed improvements in physical fitness were associated with improved cardiorespiratory endurance (Fragala-Pinkham et al., 2008), strength, flexibility, and aerobic fitness (Lochbaum & Crews, 2003; Yilmaz et al., 2004), and decreased body mass index (Pitetti et al., 2007). It is important to note that of these 4 studies, only 1 involved a TM, thus, a minimal number of studies that examined the metabolic effects a TM has on children with ASD exist and no studies exist that examined motor capabilities associated with tripping risk. It is unclear how children with ASD will motorically respond to TM-based interventions in the hopes of decreasing obesity rates.

Research examining TM-based walking in the ASD population may add more insight into understanding the motor strategies attained as previous findings observed that individuals in special populations utilize different strategies to achieve appropriate foot or toe clearance (TC), which may produce tripping (Levinger et al., 2012; Little et al., 2014). Lack of evidence investigating tripping risk to assess efficacy of TM-use in children with ASD, establishes the need for such research before metabolic measures can be considered because it is unknown how children with ASD will respond to TM walking as an external stimulus in comparison to children with NT.

STATISTICAL DESIGN

The single-subject (SS) study design is not a new analysis method, rather contemporary research has preferred to focus on group statistics to generalize results of a sample to the population (Fisher, 1922). The interest to shift from group statistics to SS analysis has surfaced in current literature where individual differences were treated as the focus of the analysis instead of the group average (Barry T. Bates et al., 2004). In human movement, inter- and intra-subject variability is now a vital component in analysis (Dufek et al., 1995). Movement patterns of individuals with ASD have previously been described as heterogenous, thus, it may be optimal to examine children with ASD with a SS approach to highlight the individual differences. Although controversy exists between SS and group designs, together they can be theorized as complementary methods. The controversy stems from issues of data analysis, external validity, and how best to answer different research questions (Kazdin, 2011). Group statistics may be appropriate to summarize and provide familiarizations to novel research topics where literature is limited, and SS analysis can be applied as a secondary analysis to reveal differences that group statistics may have missed. To the authors knowledge, this is the first study examining tripping mechanics in children with ASD on a TM; thus, a group statistical design was applied.

CHAPTER 3. METHODS

PARTICIPANTS

Nineteen participants (10 ASD, 11.2±1.55 years old, 1.58±0.12m, 60.15±14.30 kg; 9 NT, 11.78±2.11 years old, 1.60±0.15m, 55.94±17.25kg) were recruited for this study. Participants were required to be able to ambulate without the use of assistive devices such as canes, crutches, or walkers. Children with NT were age- and sex-matched to a study enrolled participant with ASD. ASD diagnosis was confirmed by documentation provided by parents of participants with ASD, such as the child's most recent Individualized Education Plan (IEP) from their school, or a diagnosis from a medical professional. NT was also verbally confirmed from parents. Prior to completing laboratory activities, written parental consent and child assent were obtained in accordance with the local Institutional Review Board and the Declaration of Helsinki.

PROCEDURES

Participants completed all study-related activities in one laboratory session. Demographic and anthropometric data (age, mass, height, and sex) were measured and recorded. Participants were instructed to wear tight-fitting clothing, which was provided by the laboratory, if necessary. Spherical 14-mm retro-reflective markers were adhered bilaterally to participants' lower extremities at the following anatomical locations: anterior superior iliac spine, posterior superior iliac spine, greater trochanter, iliac spine, medial and lateral femoral epicondyle, medial and lateral malleoli, and the base of the second toe. Additionally, three-non-collinear reflective markers were placed bilaterally over the calcaneus. Then, a single marker was placed on the sacrum for pelvic tracking. All markers were secured to the locations with hypoallergenic adhesive tape. Lastly, thermo-plastic shells with four non-collinear markers were placed bilaterally on the mid-segment aspects of the thighs and legs using elastic wraps then secured with hypoallergenic adhesive tape to the wraps.

INSTRUMENTATION

Kinematic data were obtained with a 10-camera three-dimensional motion capture system (200 Hz; Vicon Motion Systems, Ltd., Oxford, UK) interfaced to a computer running Vicon Nexus software (version 2.9.1). Participants were instructed to stand in the middle of the capture volume in the laboratory with arms extended in a "T" position for subject calibration. After calibration, participants began the trials for the over-ground (OG) gait protocol. OG gait was collected first to act as the participant's baseline in comparison to the TM gait protocol. Twelve motion trials were collected where participants were instructed to walk along a 10-meter path at self-selected pace. To characterize the previously established heterogenous movement patterns associated with ASD, velocity was not controlled to allow natural movement patterns of lower extremities to be obtained (Calhoun et al., 2011; Dufek et al., 2017; Eggleston et al., 2019.; Rinehart, Tonge, Iansek, et al., 2006; Weiss et al., 2013). Moreover, participants were instructed to walk as naturally as possible and were given reminders to do so, when necessary. Average gait velocities were calculated across all trials to be used during the TM trials. After the OG trials were completed, participants rested for 10-15 minutes, as needed, before being shown to the TM. TM gait was performed on the ActiveStep treadmill (Simbex, Lebanon, NH) interfaced to a computer running ActiveStep software to control the velocity of the TM. The previously averaged OG velocity was applied to the TM condition. However, if participants felt the TM velocity was too fast, it was decreased to ensure participants' safety and comfortability. During the TM trials, participants walked for a total of five-minutes continuously where data were collected at three different trials for 30 second intervals; (Trial 1: 1:00 to 1:30, Trial 2: 2:30 to 3:00, and Trial 3: 4:00 to 4:30 minute mark). Data were not obtained during the first minute to ensure acceleration phases were not included in data analysis.

DATA REDUCTION

Raw marker trajectories were exported from Vicon Nexus to Visual3D Biomechanical Software (C-Motion, Inc., Germantown, MD, USA). A seven-segment model was constructed from the marker trajectories to include the pelvis, and left and right thigh, leg, and foot segments. Data were smoothed with a low-pass digital Butterworth filter with a cutoff frequency of 6 Hz to remove high frequency noise from the trajectory data (Winter et al., 1974). Once variables were smoothed, variables of interest were calculated using a Cardan (*X*-*Y*-Z) rotation sequence where *X* represents the medial-lateral axis, *Y* represents the anterior-posterior axis, and *Z* represents the longitudinal axis. Variables of interest were toe clearance (TC), peak knee flexion (PKF), step length (SL), double limb support time (DBL_ST), step width (SW) and OG and TM velocities (OG_velo, TM_velo, respectively). Gait analysis has been assessed quantitatively to produce temporal-spatial and kinematic parameters such as SL, DBL_ST, SW, and velocities, to examine any deviation from normal gait patterns (Chester, 2005). TC and PKF have been previously identified as descriptors for individuals at an increased risk of tripping (Benson et al., 2018; Grindle et al., 2018). TC was computed at the lowest vertical position of the toes relative to the ground, or deck of the treadmill. Then, the mean of the OG and TM velocity was extracted for each participant. Since children with ASD display asymmetrical movement patterns between the left and right limbs, data were not collapsed between limbs for comparisons (Eggleston et al., 2017; Eggleston et al., 2018; Eggleston, et al., 2019).

STATISTICAL ANALYSIS

Although Single Subject (SS) analysis is preferred for studies acknowledging the heterogeneity of the ASD population, the current study utilized a group statistical design to determine if children with ASD responded to the TM similarly as compared to the NT control group. Statistics were conducted in this manner due to the collective lack of knowledge surrounding TM gait in children with ASD and to determine if there is a consistent group response to treadmill gait. Mean and standard deviation values were computed for each variable and were collated to a group average to create ASD and NT groups, respectively. Independent samples *t*-tests (α=0.05) were used to identify significant differences between groups in variables DBL_ST, velocities, and SW. Additionally, independent samples *t*-tests were utilized for TC, PKF, SL for each limb between ASD and NT groups. Specifically, right limbs were compared between participants with ASD and NT, and left limbs were compared between participants with ASD and NT. Paired Samples *t* -tests (α=0.05) were used to identify significant differences between conditions per group for DBL_ST, velocities, and SW. All statistical tests were performed in SPSS Software (v24 IBM Corp ©, Armonk, NY).

CHAPTER 4. RESULTS

ANTHROPOMETRICS AND DEMOGRAPHIC

The anthropometric and demographic data for both groups is presented in Table 1. Results from the independent samples *t*-test suggested that participants of ASD and NT groups were not significantly different in age (p=0.50), height (p=0.70), and body mass (p=0.57). This result confirmed groups were comparable, and the NT controls were successful matches for ASD participants.

Table. 1. Participant Anthropometrics.

	ASD (n=10)	**Control (n=9)**	***p*-value**
Age (years)	11.20±1.55	11.78±2.11	0.50
Height (m)	1.58±0.12	1.60±0.15	0.70
Body Mass (kg)	60.15±14.30	55.94±17.25	0.57

Values are mean ± standard deviation (SD) for each anthropometric variable. Asterisk (*) indicates a statistically significant difference between the two groups at $p<0.05$.

TOE CLEARANCE

A significant difference between conditions was observed for TC for both groups suggesting that TC was significantly increased during the TM condition compared with the OG condition (Figure 1). Furthermore, a significant limb difference was observed in the TM for the ASD group suggesting there was a significant increase in the left limb compared to the NT group (Figure 2).

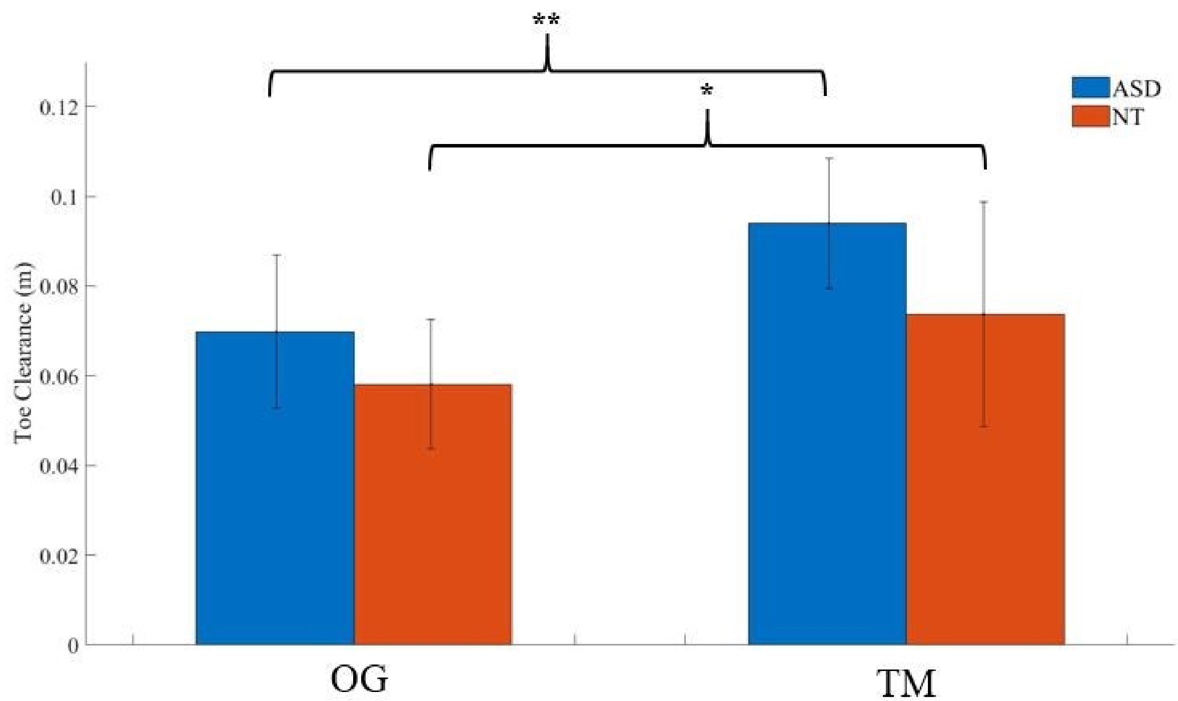


Figure 1. Mean and standard deviation values for toe clearance (meters) for ASD and NT groups during each condition. A single asterisk (*) indicates a statistically significant difference between conditions at $p<0.05$. A double asterisk (**) indicates a statistically significant difference between conditions at $p<0.001$.

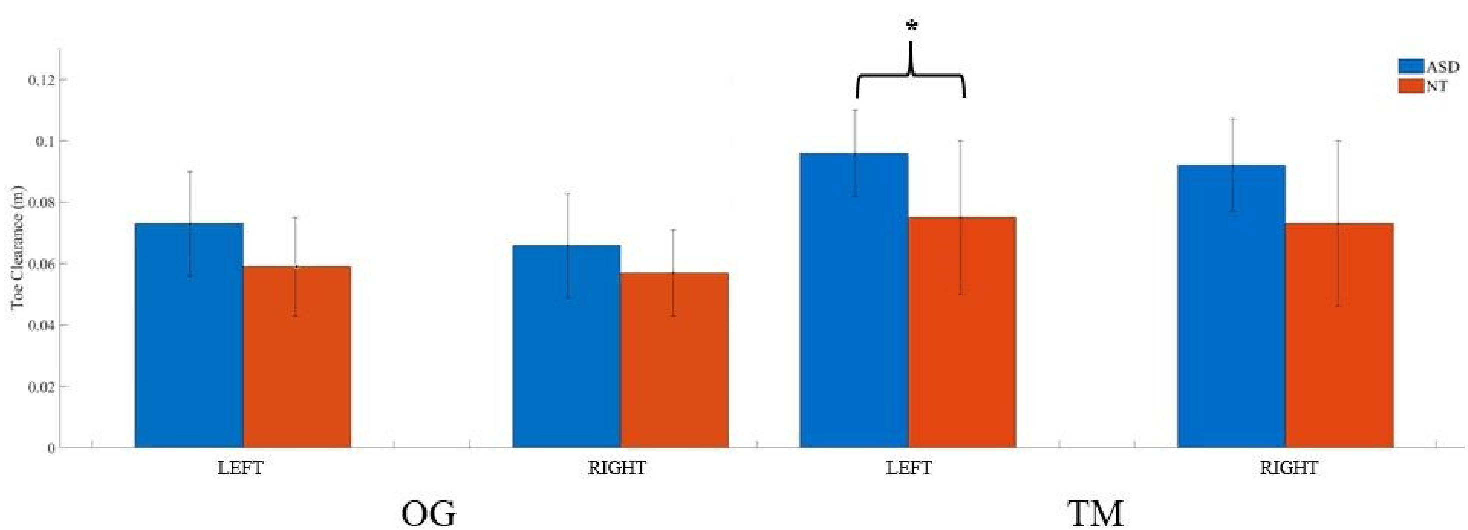


Figure 2. Mean and standard deviation values for toe clearance (meters) for each limb of both groups during each condition. A single asterisk (*) indicates a statistically significant difference between

conditions at $p<0.05$. A double asterisk (**) indicates a statistically significant difference between conditions at $p<0.001$.

TIME IN DOUBLE LIMB SUPPORT

A significant difference between conditions for DBL_ST was observed, where time spent in double limb support was statistically significantly increased during the TM condition compared with the OG condition for both groups (Figure 3).

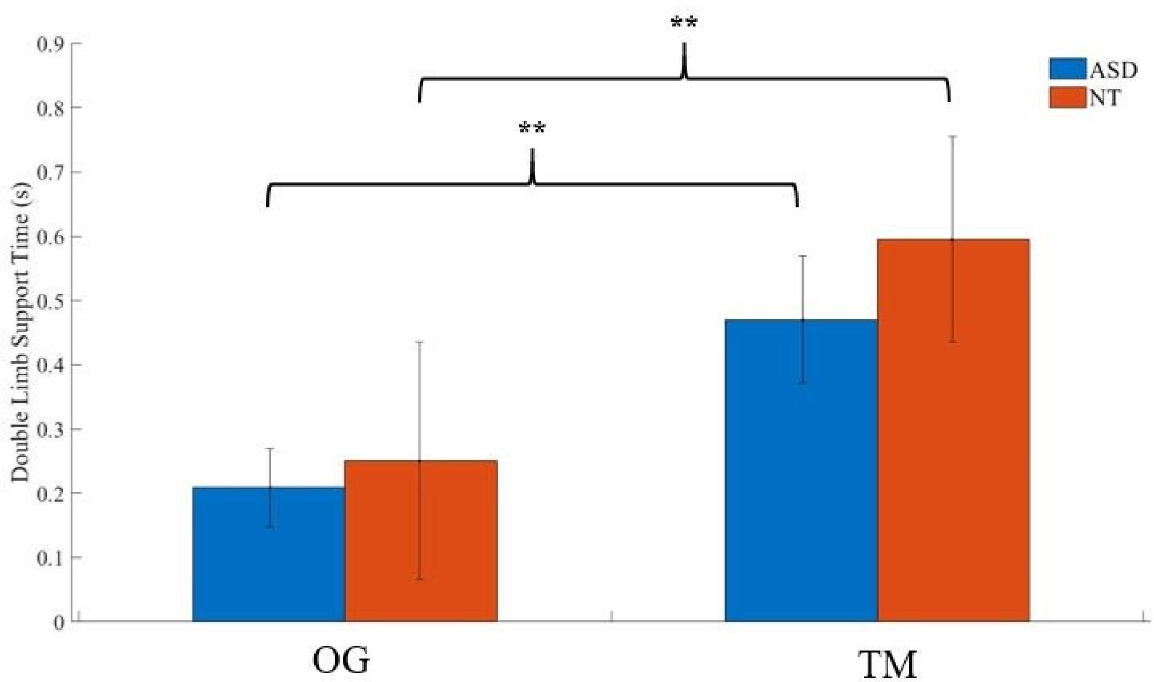


Figure 3. Mean and standard deviation values for double limb support time (seconds) for ASD and NT groups during each condition. A single asterisk (*) indicates a statistically significant difference between conditions at $p<0.05$. A double asterisk (**) indicates a statistically significant difference between conditions at $p<0.001$.

STEP WIDTH

A significant difference between conditions for step width was observed where SW was statistically significantly increased during TM condition compared with OG condition for both groups. (Figure 4).

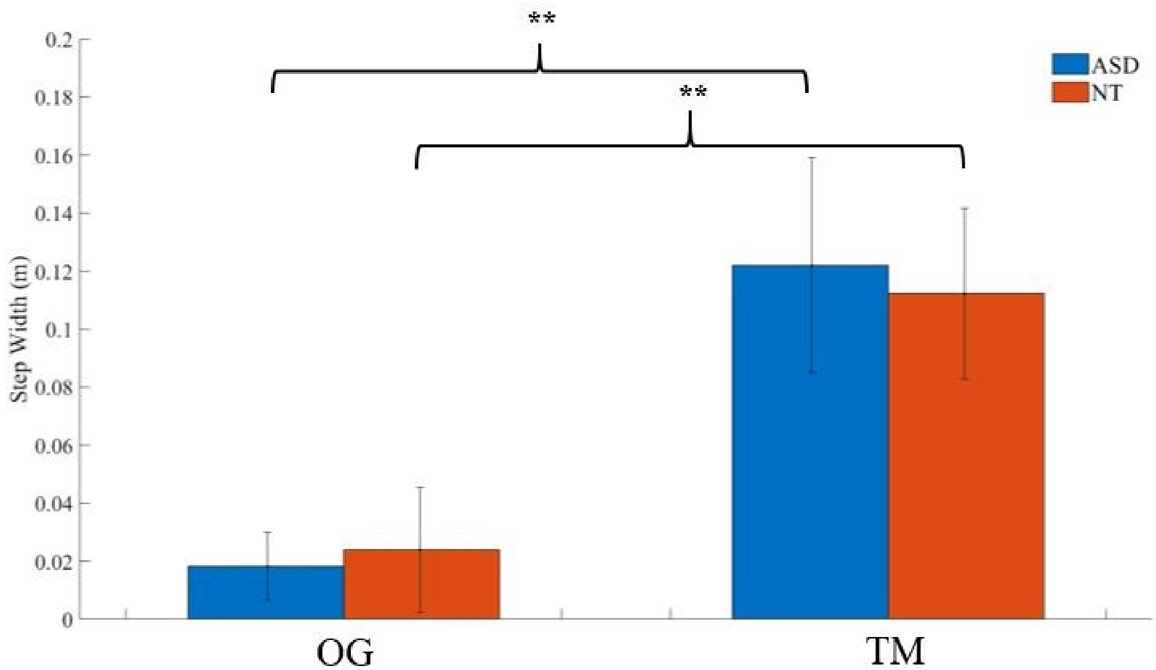
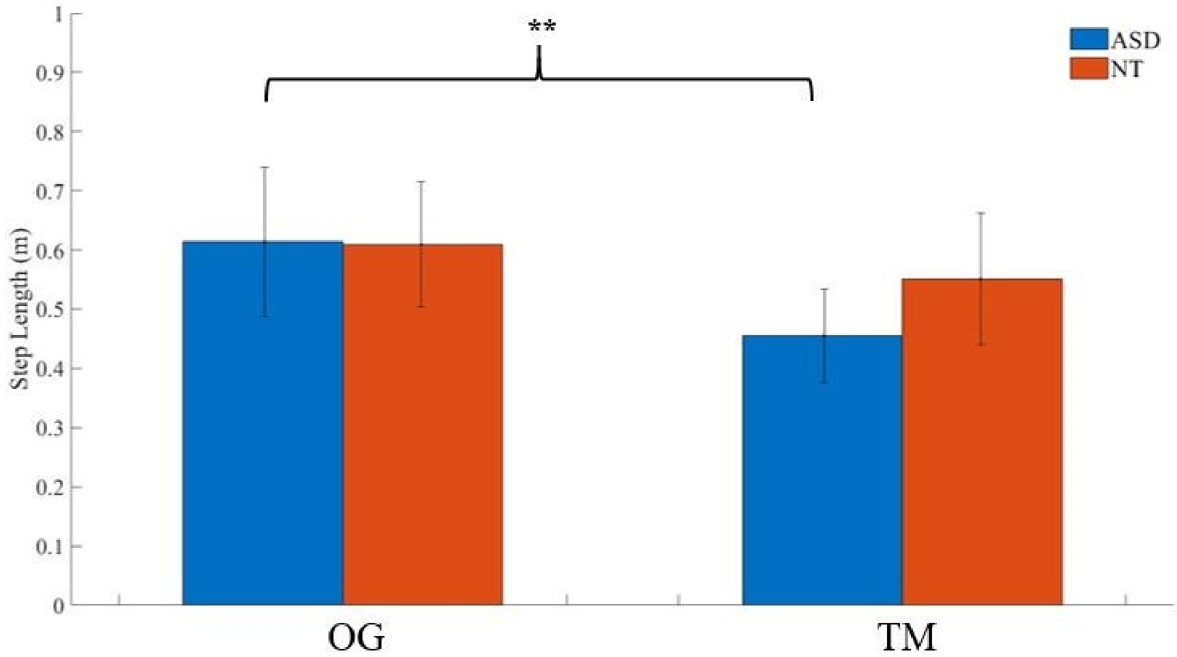


Figure 4. Mean and standard deviation values for step width (meters) for ASD and NT groups during each condition. A double asterisk (**) indicates a statistically significant difference between conditions for ASD and NT groups at $p<0.001$.

STEP LENGTH

A statistically significant difference between conditions for SL was observed only in the ASD group, where SL was significantly decreased during the TM condition compared with the OG condition (Figure 5). Additionally, there was also a statistically significant difference between left limbs during the TM condition where SL was significantly decreased for the ASD group (Figure 6).



(a)

Figure 5. Mean and standard deviation values for step length (meters) for ASD and NT groups during each condition. A double asterisk (**) indicates a statistically significant difference between conditions for ASD and NT groups at p<0.001.

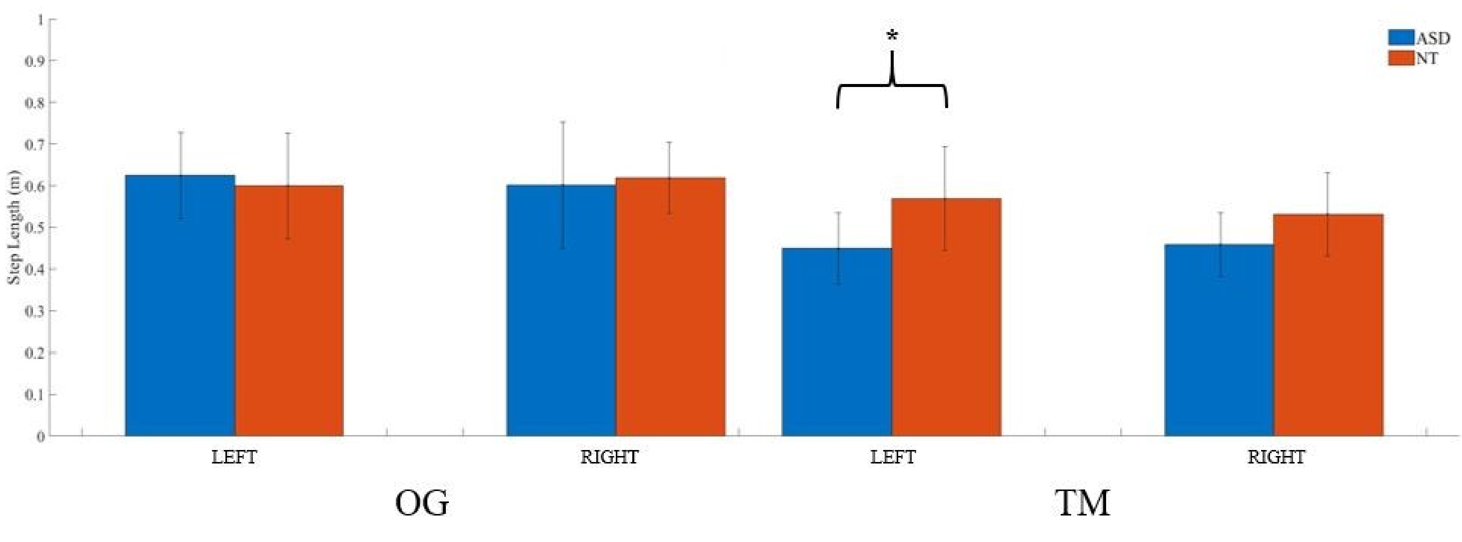


Figure 6. Mean and standard deviation values for step length (meters) for each limb of both groups during each condition. A single asterisk (*) indicates a statistically significant difference between conditions at $p<0.05$. A double asterisk (**) indicates a statistically significant difference between conditions at $p<0.001$.

PEAK KNEE FLEXION

There was no statistically significant difference observed between conditions for PKF for either group (Figure 7). Additionally, there was no statistically significant difference observed between group limbs as well (Figure 8). ASD and NT groups, thus, had similar PKF values between conditions as well as between limbs.

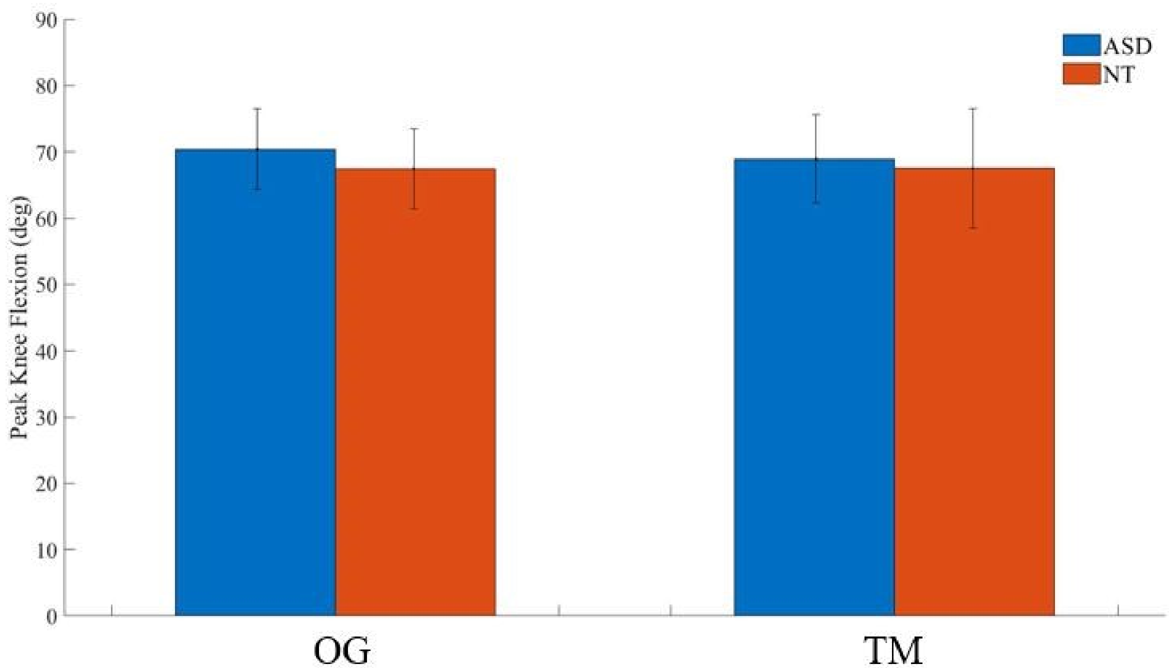


Figure 7. Mean and standard deviation values for peak knee flexion (degrees) for ASD and NT groups during each condition. A double asterisk (**) indicates a statistically significant difference between conditions for ASD and NT groups at $p<0.001$.

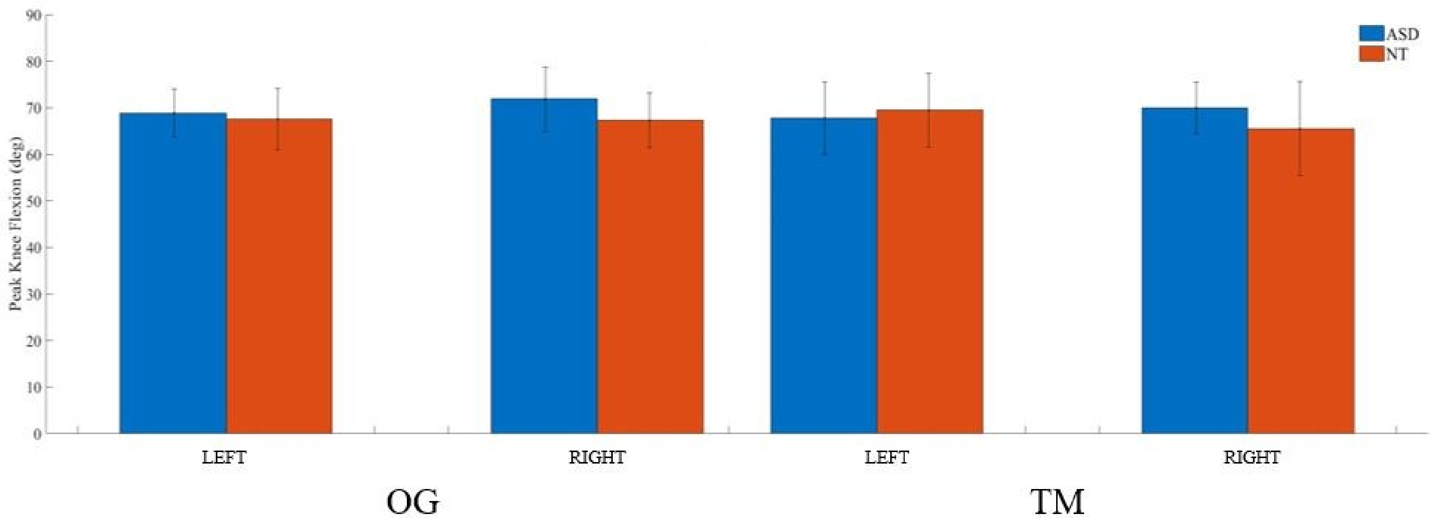


Figure 8. Mean and standard deviation values for peak knee flexion (degrees) for each limb of both groups during each condition. A single asterisk (*) indicates a statistically significant difference between conditions at $p<0.05$. A double asterisk (**) indicates a statistically significant difference between conditions at $p<0.001$.

<u>VELOCITY</u>

A significant group difference was not observed for either condition. However, the Paired Samples *t* -test revealed both groups had statistically significantly slower gait velocities at their preferred TM velocity compared with their preferred OG velocity (Figure 9).

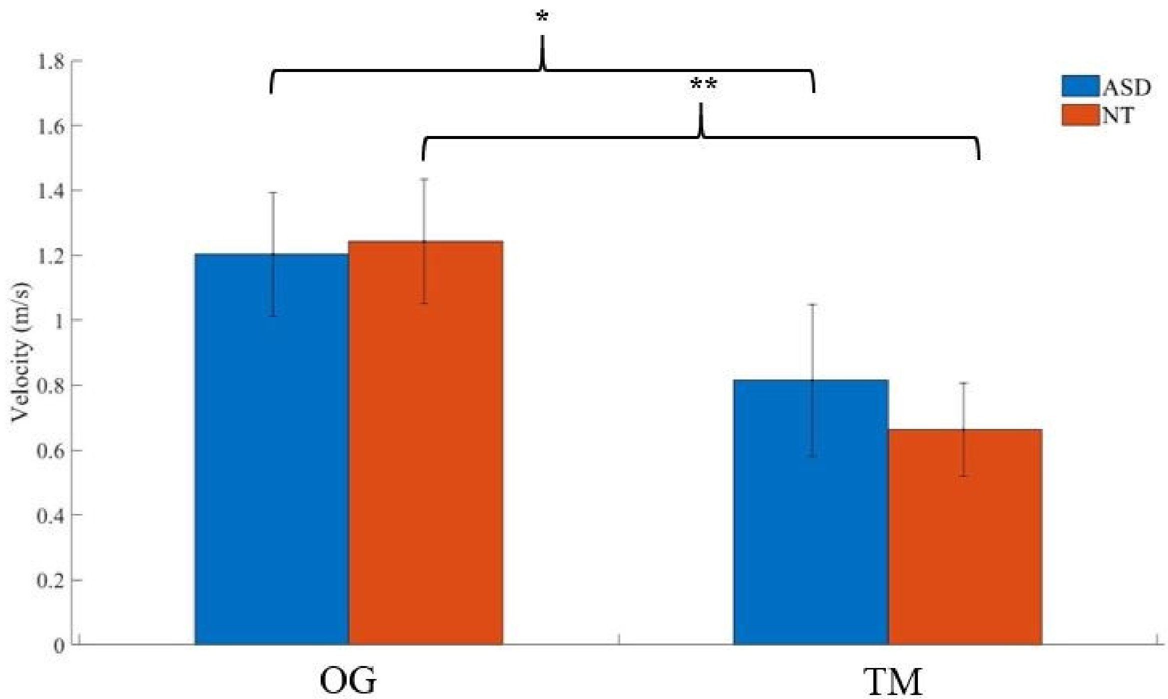


Figure 9. Mean and standard deviation values for velocity (meters/second) for ASD and NT groups during each condition. A double asterisk (**) indicates a statistically significant difference between conditions for ASD and NT groups at $p<0.001$.

<u>DISCUSSION</u>

The purpose of the current study was to examine spatial-temporal gait mechanics and lower extremity tripping descriptors between OG and TM gait conditions in children with ASD compared to children with NT. It was hypothesized that there will be differences in tripping descriptors between OG and TM conditions in the ASD population compared to NT controls. It was also hypothesized that tripping descriptors will be different between limbs between participants with ASD and NT. In general, the results of this study partially support the current hypotheses as both groups revealed mostly similar response patterns to the TM condition and statistically significant limb differences were observed in TC and SL for the ASD group. This may be due to improved dynamic stability caused by gait adaptations, or kinematic modifications, that correspond to the definition of a "cautious gait strategy" (Maki, 1997).

TRIPPING DESCRIPTORS

TC is achieved when the foot passes within 0.01m-0.02m above the ground to avoid a trip (Barrett et al., 2010; Sowa & Meulenbroek, 2012). Additionally, a pattern of diminished PKF was associated with decreased TC, leading to a trip (Goldberg et al., 2003). However, in the current study, TC values far exceeded the previous established minimal TC values in both groups during the TM condition and PKF was not diminished. This may be due to possible kinematic adaptations in the ankle or hip joints that may have elicited cautious adaptations strategies. Findings by Runge et al. (1999), described that joint torques are useful in defining postural control strategies but also affirmed that the addition of hip strategies to ankle strategies produce a "continuum of postural responses." Kuo's biomechanical model of postural control suggests that hip strategy in individuals is an effective way of stabilizing posture (Kuo, 1995; Kuo & Zajac, 1993). However, the choice of the strategy depends on the goal, and constraints proposed by the environmental (Runge et al., 1999). For example, when the goal is relative to stability optimization, such as a TM, a fast, high-amplitude response is required such as the implementation of a hip strategy, as predicted by Kuo's model (Kuo, 1995; Kuo & Zajac, 1993; Runge et al., 1999). In relation to the current study, it is possible that flexion at the hip occurred either due to torque at the hip joint, or from ankle plantarflexion paired with gravitation forces acting on the trunk, as seen in an older study (Arnold et al., 2010; Zajac, 1993) Relatively, ankle plantarflexion may had also been reduced during the swing phase for participants; as this had been observed to aid TC in preventing falls in the past (Boudarham et al., 2013). Similarly, Nagai et al. (2012) revealed that one of the characteristics of cautious gait is a reduction in ankle motion during the stance phase, due to an increase in muscle co-activation at the ankle joint. Additionally, to maintain the reduced plantarflexion, increases in the hip joints during the swing phase may had been implemented as a compensation mechanism (Boudarham et al., 2013). Thus, the ankle, knee, and hip may continually work together to correct the body while maintaining or trying to restore its equilibrium. Additionally, limb comparisons revealed left limb TC was significantly elevated during the TM condition for the ASD group only. This suggests that there may have been instances of a hip dominant movement; however, this is speculation and further analysis is needed at the hip joint to confirm. It is important to also note that both groups exhibited similar responses of increased TC values during the TM condition, despite children with ASD previously portraying heterogeneous movement characteristics compared to NT controls (Dufek et al., 2017), suggesting similar strategies were adopted. Overall, it is fair to assume neither group is more likely to experience an adverse-gait related event during the TM condition as an increased TC and unchanged PKF suggest a kinematic-adaptation strategy occurred in the ankle, knee, and hip joints consistent with cautious gait findings. Further experimentation in the ASD population is warranted to support this claim and establish new TC values during to allow researchers to quantify tripping risk, specifically during TM-use, as values do not currently exist.

SPATIAL-TEMPORAL PARAMETERS

Significant increases in DBL_ST and SW, and significant decrease in velocity were observed during the TM condition for both groups. No statistically significant difference between groups or limbs were observed for DBL_ST, OG and TM velocity, and SW.

Additionally, SL was significantly different between conditions and limbs for the ASD group during the TM condition. Where SL was significantly decreased during the TM condition compared with the NT group and left limb was decreased during the TM condition compared to the left limb of the NT group. This was consistent in previous findings, where healthy, young adults had a tendency to self-select a slower speed (Chiu et al., 2015), use shorter steps (Nagano et al., 2013), and spend less time in swing phase and more time in DBL_ST on a TM compared with OG (Alton et al., 1998; Murray et al., 1985; Yang & King, 2016). Similarly, Kautz et al. (2011) observed decreased velocity, SL, and increased stance percentage, and double-support percentage in healthy controls where post-stroke patients had similar responses but with a decreased cadence and increased step length asymmetry during TM gait. Moreover, a longer duration spent in double limb support and a greater SW had previously been observed to provide a more secure posture during gait (Espy et al., 2010). Additionally, a shortened SL suggests the center of mass of the individual may had been brought closer to the base of support providing an improved dynamic stability (Espy et al., 2010). Previously, it has been suggested that decreased gait speed had previously been associated with greater variability, and thus, greater instability (Dingwell & Marin, 2006). This falls in line with the ideology that increased locomotor variability is associated with an increased risk of falling, as previously observed in the elderly (Maki, 1997). However, these levels have not yet been examined in the ASD population. Moreover, correlation does not mean causation; a decreased gait may be better explained by adaptations to "safer" or a "more cautious" gait strategy (DeVita & Hortobagyi, 2000). Thus, it is appropriate to assume a protective gait strategy was adopted in response to the TM condition observed in both groups to preserve balance and stability. More so in the ASD group as they demonstrated decreased SL between conditions and left limbs while the NT group did not. The difference in limb comparisons suggested that there may have been instances of a hip dominant movement; however, further analysis is needed at the hip joint to confirm. Overall, the results suggest that TM may be considered the first device used for gait analysis that elicits similar responses for the most part, similar to the NT population where other authors had observed differences (Eggleston et al., 2018; Eggleston et al., 2019). The TM environment may provide adequate sensory inputs that stimulate the Central Patterns Generators within the ASD population (Dimitrijevic et al., 1998). This may be due to the lower limbs being moved backwards and behind the trunk rhythmically by the belt of the TM that provides regulatory input from the environment, thus restoring interaction within the locomotor system, as proposed in a study with Parkinson's patients (Warlop et al., 2018). Additionally, regulatory inputs from the environment had been considered crucial to overcome defective internal rhythm in basal ganglia disorders such as Parkinson's disorder (Baker et al., 2007; Nieuwboer et al., 2007; van Wegen et al., 2006). These findings may be applicable to the ASD group as ASD has been associated with basal ganglia abnormalities in the past. Thus, the sensory input from the TM may be a trigger for the ASD population, much like it was in previous literature for Parkinson's patients to maintain gait rhythmicity through gait adaptations as seen in this current study.

LIMITATIONS

Though the current study reveals interesting findings, limitations are acknowledged. First, participants were instructed to walk at a self-selected velocity during both the OG and TM conditions. As a result, all participants in both groups had a significantly slower gait during the TM trial and thus, it is unknown how tripping descriptors or spatial-temporal characteristics would have changed or remained the same if participants had walked at the same speeds during both conditions. However, the current procedures were chosen with the intent of emphasizing the participants' safety, preventing feelings of failure or inadequacy, and allowing natural movement patterns of lower extremities to be obtained, (Calhoun et al., 2011; Dufek et al., 2017; Eggleston et al., 2019.; Rinehart, Tonge, Iansek, et al., 2006; Weiss et al., 2013) especially during a novel environment such as a TM. Additionally, studies had successfully applied a previously recorded OG velocity to TM conditions, however, it had only been achieved in healthy adults (Hollman et al., 2016; Lee & Hidler, 2008; Riley et al., 2007). Nonetheless, further research in the ASD population is required to address the velocity variation concerns observed in the current study by possibly implementing a feed-back controlled treadmill (Minetti et al., 2003), and observing the effect of a safety harness during ambulation on gait dynamics (Stout et al., 2016). Secondly, although all participants were casually asked, and all answered similarly, previous use of a TM or fear of TMs were not officially recorded during the current study. Most participants had minimal to no previous experience in using a TM and it is unknown if previous experiences, or previous fears of falling off a TM may had influenced their gait during TM trials. Particularly, shorter SL, slower velocity, as well as a longer duration spent in double limb support had been previously associated with a pre-existing fear of falling in a study examining the elderly population (Maki, 1997). To combat this in future studies, authors should implement a questionnaire for parents and children describing their previous experience with a TM. Lastly, the results did not support the hypotheses possibly due to the study design as a whole. The current study utilized a group design despite past literature shifting towards a single-subject (SS) analysis that had previously established individuals with ASD displaying heterogeneous movement characteristics (Dufek, Harry, Eggleston, & Hickman, 2018), and variability proposed as a movement descriptor (Eggleston et al., 2019) suggesting each child has a unique gait pattern.

A group design may run the risk of a wash-out effect of participants with different responses to similar tasks, (Bates et al., 2016; Dufek et al., 2017) such as previous literature examining the ASD population suggests. Thus, as the ASD group portrayed similar kinematic adaptations, and strategies to the TM condition as the NT group in the current study, future research should examine the ASD group as individuals to confirm if similar responses are observed. Regardless, group statistics were appropriate to summarize and provide familiarizations to novel research topics where literature is limited, such as that of the current study.

CONCLUSION

In summary, children with ASD and NT had similar responses between conditions such as increased time in double limb support, decreased gait velocity, increased step width, and an increased toe clearance. These responses are consistent with previous findings suggesting adaptations to safer or more cautious gait strategies (Alton et al., 1998; Chiu et al., 2015; DeVita & Hortobagyi, 2000; Kautz et al., 2011; Murray et al., 1985; Nagano et al., 2013; Yang & King, 2016). However, only the ASD group displayed decreased step lengths and increased toe clearance between limbs, suggesting shorter steps were taken and a hip dominant mechanism may had occurred in the left limb. Thus, gait during TM-use may not increase tripping risk in children with ASD, but rather, may elicit strategies for safer gait, as observed in the current findings. Gait mechanics of children with ASD are still not yet fully understood as current literature had only focused on OG gait analysis in this population and TM-based studies remain sparse thus far. This study was the first to assess tripping risk during TM-use and adds to the literature of how children with ASD may respond to TM gait. Interestingly, this may had been the first study to suggest parallels to studies with Parkinson's patients suggesting TM may be a gait regulatory modality in the ASD population, however, further research is still needed to confirm. Furthermore, TM-use implemented as a future intervention, may result in reduced obesity rates, and researchers may investigate energy expenditure knowing that children with ASD may not experience a trip or fall despite previously associated motor deficits. On a global scale, establishing TMs as a trip-risk-free intervention, will allow researchers with interdisciplinary concentrations to understand the social, behavioral, neurological, physiological, and clinical effects TM gait has on the ASD population.

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CURRICULUM VITAE

Emily A. Chavez earned a Bachelor's degree in Kinesiology with a minor in Biology from The University of Texas at El Paso in Spring 2018. Soon after, in Fall 2018, she enrolled in the Maser of Kinesiology program at The University of Texas at El Paso under the supervision of Biomechanics Associate Professor, Dr. Jeffrey Eggleston. She worked as the Graduate Research Assistant and Lab Manager of the Stanley E. Fulton Gait Research & Movement Analysis lab. During the two years she assisted in multiple studies with the university's volleyball team, students from the Physical Therapy program, and undergraduate research with a walking workstation. However, her work mainly centered on the gait responses to external stimuli in children with Autism Spectrum Disorder; such as weighted devices distributed across the torso as a weighted vest, or distributed across the upper and lower limbs as ankle/wrist weights. Notably, her thesis project consisted of examining the differences between over ground and treadmill-based walking in children with Autism Spectrum Disorder compared to children with neurotypical development. For her thesis project, she had the opportunity to apply and was awarded the Dodson Research Grant in Spring 2018, to assist her recruitment process in the clinical population. Emily has a few published works in peer-reviewed journals and has presented abstract posters in internal and external conferences. She was awarded third place for Poster Presentation in the Graduate Student EXPO in 2019. Emily has also been involved community events such as the Autism Society's 10th Annual Run/Walk for Autism Awareness, and the American Society of Biomechanics National Biomechanics Day Annual Event where she holds a professional membership. Emily will graduate August 2020.

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