2022-05-01

The Mobility and Cognitive Mechanisms Involved in Altering Gait Speed in Children with Autism Spectrum Disorder

Alyssa Olivas
The University of Texas at El Paso

THE MOBILITY AND COGNITIVE MECHANISMS INVOLVED IN ALTERING GAIT SPEED IN CHILDREN WITH AUTISM SPECTRUM DISORDER

ALYSSA NICOLE OLIVAS

Doctoral Program in Biomedical Engineering

APPROVED:

Jeffrey Eggleston, Ph.D., Chair

Meagan Kendall, Ph.D.

Anita Parada, Ph.D., CBIS

Rhonda Manning, PT, DPT, PCS

Stephen L. Crites, Jr., Ph.D.
Dean of the Graduate School

THE MOBILITY AND COGNITIVE MECHANISMS INVOLVED IN ALTERING GAIT SPEED IN CHILDREN WITH AUTISM SPECTRUM DISORDER

by

ALYSSA NICOLE OLIVAS, B.S.

DISSERTATION

Presented to the Faculty of the Graduate School of

The University of Texas at El Paso

in Partial Fulfillment

of the Requirements

for the Degree of

DOCTOR OF PHILOSOPHY

Department of Metallurgical, Materials, and Biomedical Engineering

THE UNIVERSITY OF TEXAS AT EL PASO

May 2022

ACKNOWLEDGEMENTS

I would like to thank all the participants and their families for participating in this study. I appreciate them taking time out of their days to assist in the project. I would also like to thank the members of the UTEP GAIT Lab who assisted me with data collections and processing. Lastly, I would like to thank my family (Mom, Dad, Olivia) and Jacob for always supporting me throughout my journey. Their encouragement and love have given me strength to achieve all of my goals.

ABSTRACT

Autism is a socio-behavioral disorder, and diagnoses are conducted through behavioral screening instruments. Recent research suggests motor deficits may be a core symptom of the disorder, as children with autism present with deficits in motor development, locomotor skills, and postural instability. In addition, children with autism often have affected, executive function, attention, and perception cognitive domains. Different gait speeds have been used to examine gait adaptations in other clinical populations. Additionally, individuals with decreased cognitive abilities have demonstrated difficulties in modulating their walking speed. There is limited research on mechanisms children with autism use to alter their gait speed, or if cognitive abilities play a role in this task. Therefore, this multi-aim project sought to examine the mobility and cognitive mechanisms involved in altering gait speed in children with autism. Children with autism demonstrated different lower extremity angular joint positions in different speeds in the pre-swing sub-phase of gait, leading to increased hip extension, increased knee flexion, and decreased dorsiflexion at increased speeds. Large effect sizes observed in the ankle angular joint positions, suggest a primary kinematic strategy that involves the ankle when changing speed. Children with autism demonstrated no differences in dynamic stability when comparing different speeds, indicating dynamic stability is unaffected when altering gait speed. Children with autism presented with reduced cognitive abilities and slower cognitive processing. However, they did not differ from neurotypical children in their gait velocity or kinematics, indicating they mechanically alter their gait velocity, similarly to their neurotypical peers. Children with autism did not demonstrate correlations between cognitive processes and gait variables, which may indicate that children with autism are not using cognitive processes while changing their walking

speed. The findings from this study may prove beneficial, as altering gait speed is a typical task children with autism use in their daily lives.

TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

CHAPTER 1: INTRODUCTION

Autism Spectrum Disorder (ASD) affects 1 in 54 children in the United States (Maenner, Shaw, & Baio, 2020) and, as of 2015, has an estimated economic burden of $268 billion per year at the national level (Leigh & Du, 2015). ASD is typically characterized as a behavioral disorder, with core symptoms in areas of social communication and restricted and repetitive behaviors (American Psychiatric Association, 2013). Additionally, diagnosis methods primarily consist of behavioral screening instruments (Lord, Elsabbagh, Baird, & Veenstra-Vanderweele, 2018). However, past research has suggested that motor deficits may be a core symptom of the disorder (Fournier, Hass, Naik, Lodha, & Cauraugh, 2010; Matson, Matson, & Beighley, 2011), with nearly 80% of children exhibiting delays in motor milestones (Floris et al., 2016). Additionally, children with ASD present deficits in gross motor development and locomotor skills (Pan, Tsai, & Chu, 2009), such as wider step width (Nobile et al., 2011), decreased step length (Ambrosini, Courchesne, & Kaufman, 1998), slower walking speed (Lum et al., 2020), reduced range of motion at the ankle and knee joint (Ambrosini et al., 1998; Nobile et al., 2011), and increased asymmetry of the lower extremity joints during gait (Eggleston, Harry, Hickman, & Dufek, 2017) when compared to their neurotypical peers (NT)

In addition to gait, impairments in postural control and stability have been observed in individuals with ASD. Increased postural sway and decreased postural stability have been identified in individuals with ASD in multiple sensory altering conditions (Lim, Partridge, Girdler, & Morris, 2017). Most postural control studies in this population have focused on static posture (Kohen-Raz, Volkman, & Cohen, 1992; Minshew, Sung, Jones, & Furman, 2004), with

few focusing on dynamic postural control (Fournier et al., 2010). One method of quantifying dynamic stability is using margin of stability (MOS) (Hof, AL, Gazendam, & Sinke, 2005). Quantifying the MOS during gait has yet to be done in the ASD population and may yield information on how children with ASD are able to control their center of mass within their base of support during gait. If stability is compromised while walking in children with ASD, this may identify a discernable pattern in this population and a potential area in need of intervention.

While recent evidence has expanded on the deficits present in gait and stability in individuals with ASD, another area of interest in the characterization of ASD is cognitive abilities (Dichter et al., 2010; Robinson, Goddard, Dritschel, Wisley, & Howlin, 2009). It has been established that 33% of school-age children with ASD present with intellectual disabilities (IQ <70) (Maenner et al., 2020). Additionally, one third of individuals with ASD have exhibited cognitive impairments in multiple domains (Brunsdon et al., 2015). Past literature has established that executive function, perception, and attention cognitive domains may be deficient in children with ASD (Kas et al., 2014; Rajendran & Mitchell, 2007). Furthermore, it has been suggested that deficits in executive function and perception could explain the social and behavioral symptomology associated with ASD (Rajendran & Mitchell, 2007). However, there is little research aimed at understanding whether cognitive abilities impact the gross motor skills in children with ASD. It has been suggested in other populations, such as the elderly, that higher levels of cognitive impairment were associated with a poorer ability to increase speed and walk quickly (Callisaya, Michele L. et al., 2017). This indicates that populations with reduced cognitive abilities have difficulty altering their gait in response to different environments, which

in turn, may impact their daily life. However, there is little research on how the potential affected cognitive domains may play a role in gait speed in children with ASD.

Examining altering gait speed has been used in a variety of clinical populations to understand different gait patterns (Helbostad & Moe-Nilssen, 2003), variability (Yu, Riskowski, Brower, & Sarkodie-Gyan, 2009), and responses to gait perturbations (Nayate et al., 2012). Cognitive resources may play a role in an individual's ability to modify gait speed (Callisaya, Michele L. et al., 2017). Past research revealed differences in spatial temporal gait characteristics at different speeds in children with Attention Deficit Hyperactivity Disorder (ADHD) and revealed timing regulation deficits in this population (Papadopoulos, McGinley, Bradshaw, & Rinehart, 2014). Additionally, research has suggested that a reduced fast walking speed is associated with decreased levels of cognitive abilities (Deshpande, Metter, Bandinelli, Guralnik, & Ferrucci, 2009). Walking speed reserve, defined as the ability to change from preferred to fast walking speed, has been positively associated with greater cognitive abilities (Callisaya, ML, Blizzard, McGinley, & Srikanth, 2012). However, there is still little information about how children with ASD may respond to certain gait perturbations such as altering gait speed. Only one study examined fast, slow, and preferred gait speeds in children with ASD compared to NT children (Nayate et al., 2012), and focused only on spatial temporal parameters. Results revealed the ASD group displayed an increased stride width and step length in each speed condition, with the differences most evident at the preferred and slow speed. The authors attributed their findings to abnormalities in the cerebellum and fronto-striatal system, that may cause a difference in the intended and actual movements (Nayate et al., 2012). However, it is currently unknown if there are different angular joint motion strategies used in differing gait speeds in children with ASD,

and where those differences may lie. Such knowledge will give more insight in how children with ASD modulate their lower extremity joints to accommodate different speeds. Additionally, by quantifying dynamic stability during differing gait speeds, results may indicate whether children with ASD are less stable at velocities other than their preferred velocity. Lastly, it is worth investigating whether the level of the cognitive abilities impacts the capability to change gait speed in children with ASD.

Therefore, there are three current aims of this project:

1) Examine the kinematic strategies used by children with ASD in all three speeds (preferred, fast, and slow). It is hypothesized that children with ASD will demonstrate different kinematic strategies in each of the speeds, due to the cerebellar abnormalities that are present in this population that may affect their performance of an intended and actual motor task.

2) Quantify dynamic stability in children with ASD in all three speeds. It is hypothesized that children will demonstrate decreased stability during the fast and slow walking speed, as children with ASD demonstrate differences in kinematic strategies during speeds that deviate from their preferred speed

3) Examine the relationships between cognitive abilities and the ability to increase walking speed in children with ASD. It is hypothesized that children with ASD will present decreased cognitive abilities than NT, and those with reduced processing speed, attention, and executive functions will have a slower walking speed, lower walking speed reserve, and different kinematic strategies.

CHAPTER 2: CHILDREN WITH AUTISM UTILIZE AN ANKLE JOINT STRATEGY WHEN ALTERING GAIT SPEED

INTRODUCTION

Understanding how individuals alter their gait speeds has been used in different clinical populations to understand different gait patterns (Helbostad & Moe-Nilssen, 2003) variability (Yu, Riskowski, Brower, & Sarkodie-Gyan, 2009), and responses to gait perturbations (Nayate et al., 2012). Most studies in this area have focused on adults with neurological impairments, including those with multiple sclerosis (MS; (Remelius et al., 2012), Parkinson's Disease (Cole, Sweeney, Conway, Blackmore, & Silburn, 2017; Morris, Iansek, Matyas, & Summers, 1994), dementia (Callisaya, Michele L. et al., 2017), and Alzheimer's Disease (Webster, Merory, & Wittwer, 2006). However, there have been few studies on children with neurological impairments, specifically on children with Autism Spectrum Disorder (ASD) who often exhibit variable walking patterns (Lum et al., 2020; Nayate et al., 2012).

ASD is categorized as a socio-behavioral disorder, with associated symptomology of communication deficits, social interaction deficits, and repetitive and restricted movements (American Psychiatric Association, 2013). Recent evidence suggests that ASD may also present as a movement disorder, as many individuals display deficits in locomotor skills and gross motor development (Floris et al., 2016; Fournier et al., 2010; Matson et al., 2011). Deficits in gross motor skills can impact daily life and lead to clumsy movement patterns during gait (Manicolo, Brotzmann, Hagmann-von Arx, Grob, & Weber, 2019). Additionally, past neurological studies indicate that the motor cortex, supplementary motor area, basal ganglia, and cerebellar

abnormalities may play a role in the observed motor deficits in this population (Fournier et al., 2010).

Children with ASD have presented with spatial-temporal and kinematic differences during gait, when compared to their neurotypical (NT) peers. These distinct characteristics include an increased stride width (Nayate et al., 2012; Nobile et al., 2011; Shetreat-Klein, Shinnar, & Rapin, 2014), decreased step length (Ambrosini et al., 1998; Nobile et al., 2011; Vernazza-Martin et al., 2005; Vilensky, Damasio, & Maurer, 1981; Weiss, Moran, Parker, & Foley, 2013), slower stride velocity (Ambrosini et al., 1998; Nobile et al., 2011; Weiss et al., 2013), longer gait cycle, and increased stance and step time (Lum et al., 2020). It has been suggested that the observed differences are a subconscious effort to increase stability in this population (Kindregan et al., 2015). Individuals with ASD demonstrate reduced ankle joint range of motion (Ambrosini et al., 1998), reduced plantarflexion at toe-off (Nobile et al., 2011), reduced range of motion at the knee at toe-off (Nobile et al., 2011), and reduced knee extension at the initial contact phase of gait (Vilensky et al., 1981). Children with ASD have also displayed increased ankle joint stiffness, which may be attributed to an inefficient propulsion force during gait (Eggleston, Harry, & Dufek, 2018). Additionally, children with ASD have exhibited asymmetry in the lower extremity joint positions during gait (Eggleston et al., 2017).

The majority of gait analysis studies in the ASD population have used a preferred walking speed (Dufek, Eggleston, Harry, & Hickman, 2017; Eggleston et al., 2017; Eggleston, Landers, Bates, Nagelhout, & Dufek, 2018; Eggleston et al., 2020; Nobile et al., 2011; Vilensky et al., 1981).

There has been only one study previously done on preferred, fast, and slow gait speeds in children with ASD when compared to NT children (Nayate et al., 2012), which only examined spatial-temporal characteristics. The findings revealed that base of support was increased in all three gait speeds in children with ASD, compared to NT controls (Nayate et al., 2012). The authors suggested this was connected to cerebellar abnormalities that are often found in this population (Rinehart, Tonge, Iansek et al., 2006). Additionally, children with ASD presented with increased stride length at all speeds, mostly at the slow and preferred walking speeds, when compared to children with NT. This finding differs from a pathological parkinsonian gait pattern of decreased stride length at various cadences and may suggest children with ASD have a motor deficiency causing a discrepancy between the intended and actual movement (Nayate et al., 2012). The authors suggest this could be credited to abnormalities present in the fronto-striatal system that is causing increased adjustment of the intended movement. Past studies have identified atypical pre-movement cortical activity in children with ASD (Rinehart, Tonge, Bradshaw et al., 2006). However, it is currently unknown what angular joint motion strategies are used in differing gait speeds in children with ASD. Such knowledge will give more insight in how children with ASD modulate their lower extremity joints when changing their gait speed. Therefore, the purpose of the current study is to examine the kinematic strategies used by children with ASD in preferred, fast, and slow walking speeds. It is hypothesized that children with ASD will demonstrate different kinematic strategies in each of the speeds, due to the cerebellar abnormalities that are present in this population that may affect their performance of an intended and actual motor task.

METHODS

Participants

An a priori power analysis (G*Power 3.1, Dusseldorf, Germany) was performed using data from (Nayate et al., 2012) to determine sample size. Based on an effect size of 0.98, power of 0.8, and significance level of 0.05, it was established that a sample size of 14 would provide sufficient statistical power. A sample of 14 children with ASD between the ages of 8-17 participated in the study. A clinical diagnosis of ASD was confirmed with documentation from a medical professional, or with an Individualized Education Program (IEP) for the child's school. All children were required to be free from any orthopedic condition/disorder which may further impair their ability to walk.

Instrumentation

Participants were instrumented with spherical 14 mm retro-reflective markers, bilaterally, on the anterior superior iliac spines, posterior superior iliac spines, greater trochanters, iliac crests, medial and lateral femoral condyles, medial and lateral malleoli, and base of the second toe. Three-non-collinear reflective markers were placed bilaterally over the calcaneus. A single marker was placed on the sacrum for pelvis tracking. Additionally, thermo-plastic shells with four non-collinear marker clusters were placed on the lateral aspect, mid-segment of the thighs and legs using elastic wraps. Kinematic data were collected with a 10-camera three-dimensional motion capture system (200 Hz; Vicon Motion Systems, Ltd., Oxford, UK).

Protocol

Anthropometric data was collected, and participants began by walking over-ground at their preferred self-selected speed and reminded to walk as naturally as possible, when needed. The

order of the two experimental conditions, fast and slow speed, were randomized among participants. For the fast speed, participants were instructed to walk faster than their preferred speed and discouraged from running; trials were discarded if participants ran. For the slow speed, participants were asked to walk slower than their preferred speed. Velocity was monitored during all conditions using Brower Timing Gates (Brower Timing Systems, Draper, UT, USA) placed five meters apart. Twelve motion capture trials were collected for each condition for a total of 36 trials, and participants were given breaks when necessary.

Data Analysis

Raw kinematic data were exported to Visual 3D Biomechanical Software Suite (C-Motion, Inc., Germantown, MD, USA) for further analysis. Marker trajectories were smoothed using a low-pass Butterworth digital filter (6 Hz) to remove high frequency noise. A seven-segment model was constructed from the smoothed marker trajectories including the pelvis and bilateral thigh, leg, and foot segments. All data were normalized to 100% of the gait cycle (101 data points). Heel strike and toe-off events were identified using a velocity-based algorithm (Zeni Jr, Richards, & Higginson, 2008). Variables of interest include bilateral hip, knee, and ankle angular position in the sagittal plane. Gait velocity in all three conditions were obtained using the times from the timing gates. The gait cycle was divided into seven sub-phases (Rancho Los Amigos National Rehabilitation Center, 2001) as a percentage of the gait cycle; the current study will focus on loading response (LR) (0–10% of the gait cycle), pre-swing (PSw) (51–60% of the gait cycle), and terminal swing (TSw) (88–100% of the gait cycle) sub-phases for bilateral angular joint positions. LR and TSw were focused on due to past literature revealing that body forward propulsion of the lower extremities when changing gait speed occurred during early stance and

late swing (Riley, Della Croce, & Kerrigan, 2001). PSw was used due to this sub-phase playing a role in limb advancement and weight transfer (Kharb, Saini, Jain, & Dhiman, 2011).

Statistical Analysis

For gait velocity, analysis of variance (ANOVA) with repeated measures (α=0.05) was conducted, and pairwise comparisons were interpreted after applying the Sidak adjustment. Repeated measures ANOVAs were conducted to test for significant differences (α=0.05) for each sub-phases between the three speeds for bilateral lower extremity angular positions. If significance was detected in the omnibus ANOVA test, pairwise comparisons were interpreted after applying the Sidak adjustment. The assumption of sphericity was tested with Maulky's test for sphericity for all tests, and if the assumption of sphericity was violated, the Greenhouse-Geisser estimate was used. Effect sizes were calculated as partial eta squared (η^2) and interpreted with Cohen's scale (Cohen, 1988). Limbs were not collapsed due to past research determining asymmetry between the limbs in children with ASD (Eggleston et al., 2017; Eggleston et al., 2018).

RESULTS

Anthropometrics and Gait Velocity

A total of 14 children with ASD participated in the study (2 females, 12 males, age: 11.64 ± 2.13 years, height: 1.55 ± 0.15 meters, mass: 54.4 ± 20.16 kg). Analysis revealed significant differences among gait velocity in each of the three conditions, ($F(_{1.23,\ 15.98}) = 144.57$, $p<0.001$, $\eta^2= 0.92$). After applying the Sidak adjustment, significant differences were found between the

fast and preferred velocity (p<0.001), between the preferred and slow velocity (p<0.001), and between the fast and slow velocity (p<0.001). (**Table 2.1**)

Table 2.1. Mean Gait Velocities Among Speed Conditions

	Preferred	**Fast**	**Slow**
Velocity (m/s) *	1.06 ± 0.13	1.41 ± 0.16 ✦•	0.72 ± 0.16 ♦•
Percent Change		+33.63 ± 10.09%	-32.43 ± 12.15%

Mean and (±) standard deviation values for gait velocity at each speed. Percent change from preferred velocity is included. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

Hip Angular Joint Positions

Significant differences were not revealed in the left hip angular joint positions among conditions in LR ($F_{(1.31,17.01)}$ =1.84, p=0.178, η^2=0.12). The left hip showed a significant difference and small effect size in the PSw sub-phase ($F_{(2,26)}$ = 8.02, p= 0.002, η^2= 0.38), with significant pairwise comparison between the fast and slow condition (p=0.01), while the comparison between the fast and preferred (p=0.06) and the preferred and slow (p=0.56) conditions were not significant. There was a significant difference and small effect size in left hip in the TSw sub-phase ($F_{(2,26)}$ = 5.32, p=0.01, η^2= 0.29). There was a significant pairwise comparison between the fast and slow condition (p=0.01) and the preferred and slow (p=0.01) conditions, while the comparison between the fast and preferred (p=0.70) was not significant. (**Figure 2.1**)

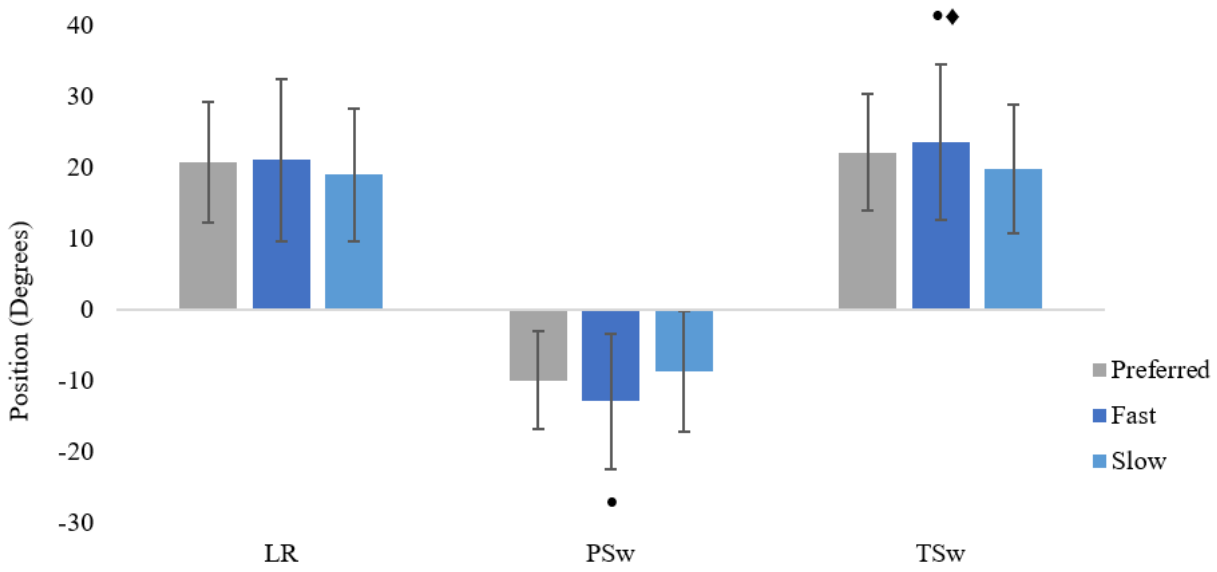

Figure 2.1. Mean and standard deviation for left hip angles at preferred, fast, and slow conditions at each sub-phase. (LR: Loading Response, PSw: Pre-swing, TSw: Terminal Swing). Positive values indicate flexion. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

For right hip angular joint positions, there was not a significant difference revealed for LR ($F_{(1.18,15.37)} = 0.64$, p=0.46, η^2= 0.05) In PSw, the right hip showed a significant difference and small effect size among conditions ($F_{(2,26)} = 7.91$, p=0.002, η^2= 0.38), with pairwise comparisons revealing a significant difference between fast and slow (p=0.01), and no significant comparison between fast and preferred (p=0.05) or preferred and slow (p=0.74). In TSw, there were significant differences and small effect size among the conditions ($F_{(2,26)} = 5.16$, p=0.01, η^2= 0.28), and a significant pairwise comparison between fast and slow (p=0.03). Comparisons between fast and preferred (p=0.55) and between preferred and slow (p=0.07) were not significant. (**Figure 2.2**)

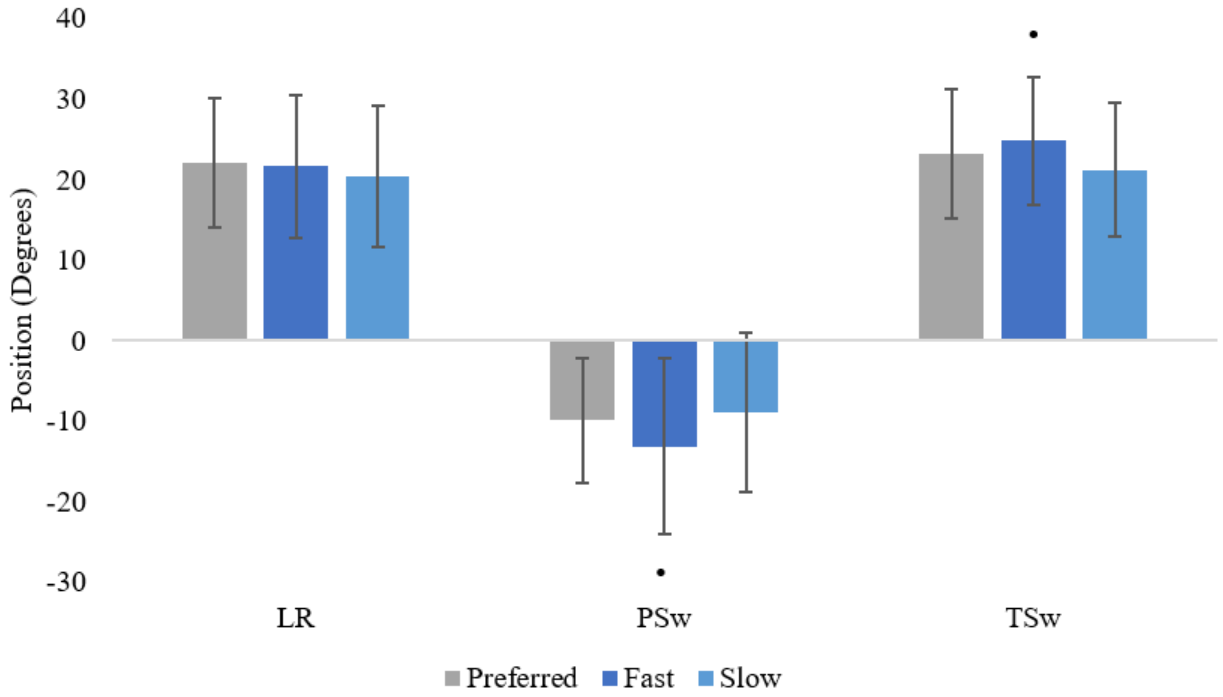

Figure 2.2. Mean and standard deviation for right hip angles at preferred, fast, and slow conditions at each sub-phase. (LR: Loading Response, PSw: Pre-swing, TSw: Terminal Swing). Positive values indicate flexion. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

Knee Angular Joint Positions

During LR, the omnibus ANOVA revealed a significant difference and moderate effect size in the left knee among conditions ($F_{(2,26)} = 15.26$, p<0.001, η^2=0.54). Pairwise comparisons revealed a significant difference between fast and slow conditions (p<0.001). However, there was no significant pairwise comparison between fast and preferred (p=0.07) or between preferred and slow (p=0.05) conditions. The left knee demonstrated a significant difference and moderate effect size in PSw among conditions ($F_{(1.38, 17.89)} = 23.95$, p<0.001, η^2=0.65). Pairwise comparisons revealed significant differences between fast and preferred (p=0.004), between preferred and slow (p=0.002), and between fast and slow (p<0.001) conditions. In TSw, the left

knee did not show a significant difference among the three conditions, ($F_{(2,26)} = 1.79$, p=0.19, η^2=0.12). (**Figure 2.3**)

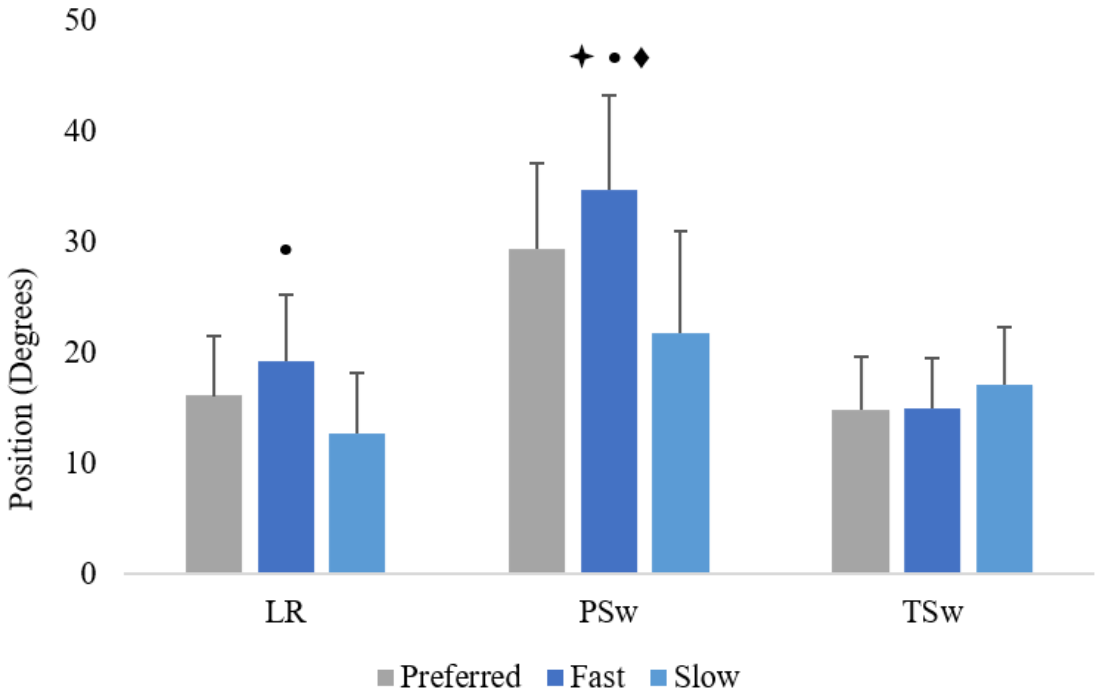

Figure 2.3. Mean and standard deviation for left knee angles at preferred, fast, and slow conditions at each sub-phase. (LR: Loading Response, PSw: Pre-swing, TSw: Terminal Swing). Positive values indicate flexion. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

Analysis of the right knee revealed a significant difference and small effect size in LR among the conditions ($F_{(2,26)} = 10.68$, p<0.001 , η^2=0.45), with significant pairwise comparisons between preferred and slow (p=0.02), and between fast and slow (p=0.005), but not between fast and preferred (p=0.15). The PSw sub-phase revealed a significant difference and moderate effect size in the right knee among conditions ($F_{(2,26)} = 25.76$, p<0.001 , η^2= 0.67), and significant pairwise comparisons between all conditions (fast and preferred: p=0.01; preferred and slow: p=0.002; fast and slow: p<0.001). In TSw, the right knee displayed a significant difference and small

effect size among conditions ($F_{(2,26)} = 4.21$, $p=0.03$, $\eta^2=0.25$). However, there were no significant pairwise comparisons (fast and preferred: $p=0.70$; preferred and slow; $p=0.09$; fast and slow $p=0.19$). (**Figure 2.4**)

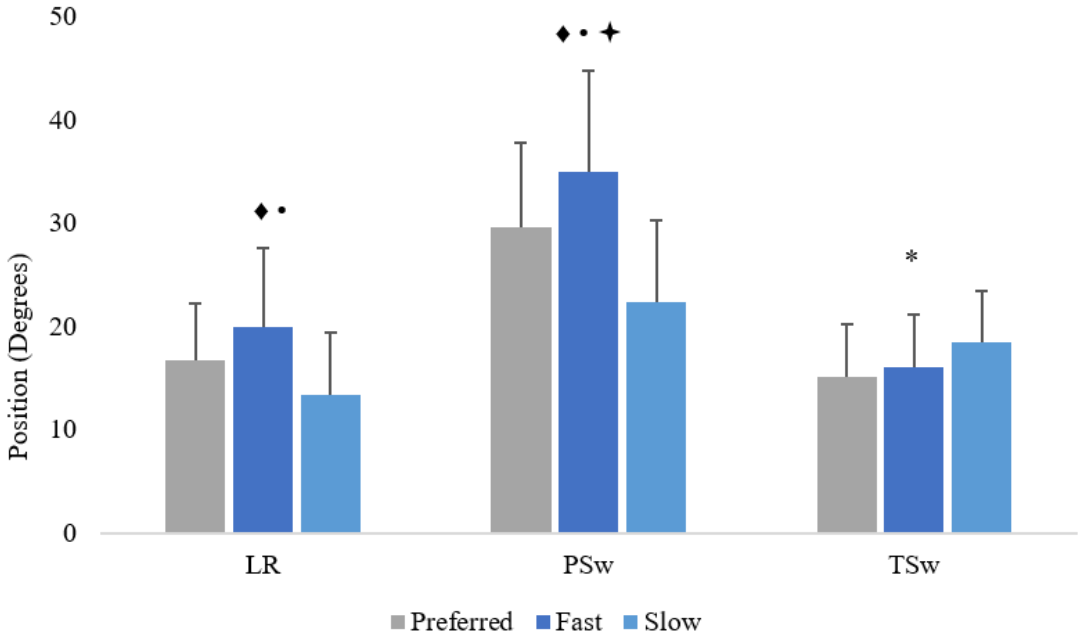

Figure 2.4. Mean and standard deviation for right knee angles at preferred, fast, and slow conditions at each sub-phase. (LR: Loading Response, PSw: Pre-swing, TSw: Terminal Swing). Positive values indicate flexion. Asterisk (*) indicates a statistically significant ($p<0.05$) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

Ankle Angular Joint Positions

The left ankle revealed no significant differences among conditions in LR ($F_{(2,26)} = 3.29$, $p=0.05$, $\eta^2=0.20$) or in TSw ($F_{(2,26)} = 0.208$, $p= 0.81$, $\eta^2= 0.02$). In PSw, the left ankle demonstrated significant differences and moderate effect size among the three conditions ($F_{(2,26)} =31.66$, $p<0.001$, $\eta^2=0.71$), with significant pairwise comparisons between all conditions (fast and preferred: $p<0.001$; preferred and slow: $p=0.01$, and fast and slow $p<0.001$). (**Figure 2.5**)

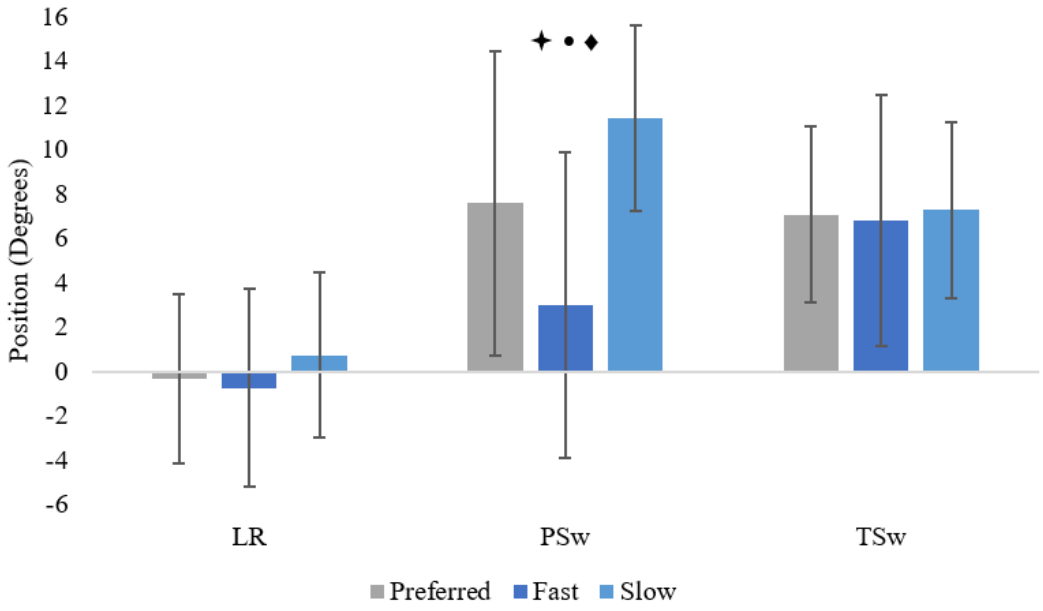

Figure 2.5. Mean and standard deviation for left ankle angles at preferred, fast, and slow conditions at each sub-phase. (LR: Loading Response, PSw: Pre-swing, TSw: Terminal Swing). Positive values indicate dorsiflexion. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

The right ankle revealed a significant difference and small effect size among conditions in LR ($F(_{2,26}) = 3.90$, p=0.03, η^2= 0.23); however, there were no significant pairwise comparisons (fast and preferred: p=0.99; preferred and slow: p=0.13; fast and slow: p=0.10). The right ankle revealed significant differences and large effect size among conditions in PSw ($F(_{1.37,17.83}) = 51.82$, p<0.001, η^2=0.80) and demonstrated significant pairwise comparisons in all three conditions (fast and preferred: p<0.001; preferred and slow: p<0.001; between fast and slow: p<0.001). There were no significant differences in the right ankle during TSw among the conditions ($F(_{2,26}) = 0.22$, p=0.80, η^2= 0.02). (**Figure 2.6**)

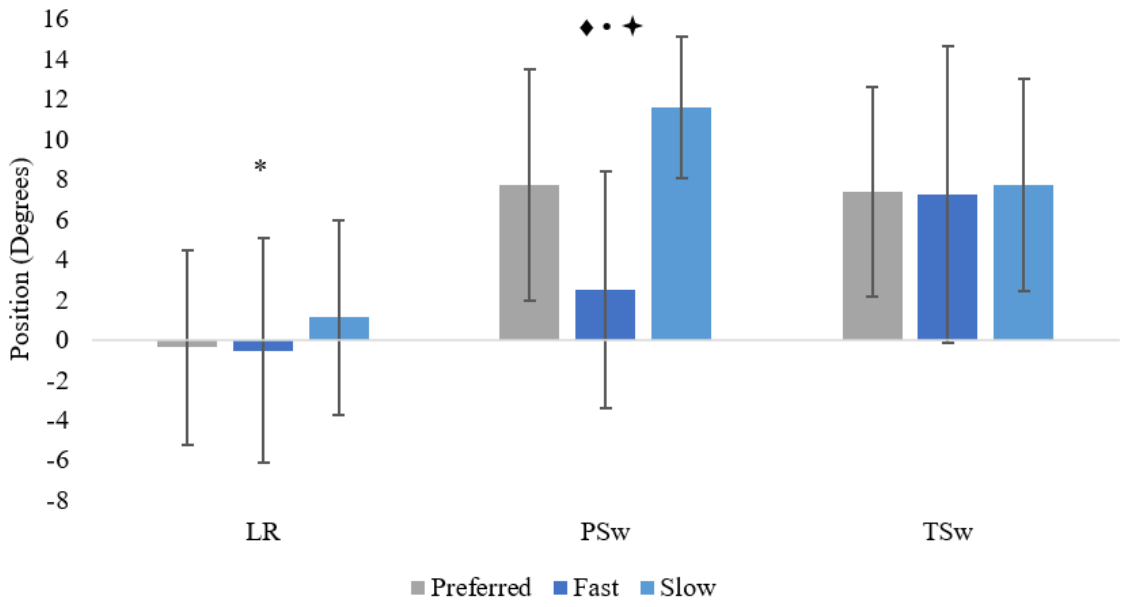

Figure 2.6. Mean and standard deviation for right ankle angles at preferred, fast, and slow conditions at each sub-phase. (LR: Loading Response, PSw: Pre-swing, TSw: Terminal Swing). Positive values indicate dorsiflexion. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

DISCUSSION

The purpose of the current study was to examine the kinematic strategies used by children with ASD in preferred, fast, and slow walking speeds. The hypothesis that different kinematic strategies would be used at different speeds was supported, as there were differences among bilateral lower extremity angular joint positions observed in children with ASD. The current study focused on LR, PSw, and TSw gait sub-phases. LR revealed increased flexion of the knee at the fast speed, and TSw revealed increased flexion of the hip at the fast speed. However, the only sub-phase which demonstrated changes in each of the angular joint positions among all three speeds with moderate to large effect sizes was the PSw sub-phase, which revealed

increased hip extension, increased knee flexion, and decreased dorsiflexion at increased speeds for children with ASD. These findings suggest that PSw may play a critical role in how children with ASD alter their gait speed. This sub-phase in the end of stance phase is associated with limb advancement and the abrupt transfer of body weight (Kharb et al., 2011). Additionally, PSw is associated with increased ankle plantar flexion, greater knee flexion and decreased hip extension (Kharb et al., 2011). Children with ASD demonstrated increased hip extension at a faster speed, which may be in response to a change from their non-preferred gait speed leading to a shorter duration of LR and PSw sub-phase, which comprise double limb support (Stansfield, Hillman, Hazlewood, & Robb, 2006).

Historically, research suggests that hip, knee, and ankle angular joint positions do not significantly differ among different walking speeds (Winter, 1983). However, consistent with the current study, more recent research on neurotypical children revealed significant changes in lower extremity joint angles in response to various gait speeds (van der Linden, Mariëtta L, Kerr, Hazlewood, Hillman, & Robb, 2002). Additionally, past literature has presented significant correlations of peak lower extremity joint angles with gait speed (Hanlon & Anderson, 2006; Lelas, Merriman, Riley, & Kerrigan, 2003). More specifically, increased knee flexion showed a positive correlation with gait speed. While the current study examined angular joint positions at sub-phases, an increased knee flexion was revealed with increased gait speed and decreased knee flexion was observed in slower gait speed in LR and PSw. This observation could be due to greater shock absorption at faster speeds (Hanlon & Anderson, 2006). Additionally, children with ASD demonstrated decreased knee flexion, increased dorsiflexion at slower speeds, which

is consistent with previous literature (Fukuchi, Fukuchi, & Duarte, 2019), which indicates that children with ASD may exhibit similar angular joint strategies as NT children at slower speeds.

Recent research suggests that a faster gait speed requires larger propulsive forces (Hebenstreit et al., 2015), and most of the propulsive strategies that are utilized when changing gait speed occur predominately at the hip and the ankle (Riley et al., 2001). Hip muscles and range of motion are important to propulsion during gait. While the current study revealed significant changes in hip range of motion during PSw and TSw, the effect sizes were small, indicating that may not be the main kinematic strategy utilized by children with ASD when changing gait speed. Additionally, neurotypical children have demonstrated decreased hip flexion at decreased speeds (Fukuchi et al., 2019), while children with ASD exhibited increased hip flexion during PSw sub-phase in the current study. This finding also suggests that the hip joint may not play as critical a role in changing gait speed in children with ASD. The differences observed in the ankle during PSw had the largest effect size for children with ASD in the current study. The ankle has been shown to provide support to upper body mass during the stance phase of gait and plays a role in propulsion, particularly at slower speeds (Riley et al., 2001). At slow speeds, research suggests that the plantarflexor moment of the ankle could play a larger role in propulsion (Riley et al., 2001). However, past research in neurotypical children has demonstrated that ankle joint power remained constant among different speeds and was less important to propulsion with increased speeds (Chen, Kuo, & Andriacchi, 1997). This could be of importance in the ASD population, as children with ASD have demonstrated a slower preferred walking speed in past literature (Ambrosini et al., 1998; Nobile et al., 2011; Weiss et al., 2013). The significant differences and large effect sizes observed in angular ankle joint position while changing speeds may indicate

that the ankle is the most critical part of changing speed for children with ASD. This may pose concern as children with ASD have demonstrated reduced range of motion at the ankle (Ambrosini et al., 1998) and increased ankle joint stiffness (Eggleston et al., 2018), suggesting inefficient generation of propulsive impulse. Therefore, if ankle function is compromised then support and propulsion could be altered, demanding for other joints to compensate (Riley et al., 2001).

Limitations

The current study has limitations including not controlling for physical activity level among participants, which may have impacted their ability to walk fast. However, participants were given breaks between each condition and when needed. Additionally, participants were not all independently diagnosed by the research team, but parents were required to supply physician documentation of an ASD diagnosis. Another possible limitation is the large standard deviation values observed in each of the angular joint positions. This may be the result of natural inter- and intra- individual variability during gait, and the heterogenous nature of gait in the ASD population (Dufek et al., 2017; Eggleston et al., 2017). The current study focused on a within-subjects group analysis in attempt to identify similarities among the ASD group, which could serve as a basis for future studies and interventions.

CONCLUSION

In conclusion, the current study sought to understand the different lower extremity kinematic strategies utilized by children with ASD when changing their gait speed. After evaluation of LR, PSw, and TSw sub-phases of gait, it was revealed that PSw had the significant differences

among all lower extremity angular joint positions examined, including the hip, knee, and ankle bilaterally. This may be due to the primary role of this sub-phase in limb advancement. Additionally, the ankle demonstrated the largest effect sizes when comparing different gait speeds. This indicates that the ankle may be the primary kinematic strategy used in children with ASD, providing support and aiding in propulsion when changing their gait speed. However, this may be of concern for children with ASD, as they have demonstrated reduced range of motion in the ankle and increased ankle joint stiffness. Understanding how children with ASD perform in regard to kinematic data at various gait speeds could play a role in rehabilitation settings, as normative data has not yet been established for different speeds for this population. It has also been suggested that comparing pathological gait to healthy individual gait may not be as appropriate, as those with disabilities tend to walk slower (Fukuchi et al., 2019). It is important to understand how kinematic variables are affected by gait speed in certain pathological populations. This study may serve as normative kinematic data for children with ASD in a clinical setting, with interventions focusing on the ankle when working on gait and locomotion.

CHAPTER 3: DYNAMIC STABILITY IS NOT ALTERED IN VARIOUS GAIT SPEEDS IN CHILDREN WITH AUTISM

INTRODUCTION

Autism Spectrum Disorder (ASD) is typically diagnosed by impairments in communication and social deficits, and repetitive and restricted behaviors (American Psychiatric Association, 2013). In addition to the behavioral symptoms associated with autism, children with ASD often displayed deficits in postural control and stability (Fournier et al., 2010; Lim et al., 2017). Past research has revealed that individuals with ASD demonstrate reduced postural stability with their eyes closed (Minshew et al., 2004), and under conditions when a sensory input is eliminated or altered (Kohen-Raz et al., 1992). Additionally, a recent review and meta-analysis by Lim et al. (2017) found increased postural sway in individuals with ASD in all sensory conditions, and greater variability with changes in sensory stimuli. However, a study by Fournier et al. (2010) found that children with ASD may even display impaired postural control during quiet stance without altering sensory input. Additionally, children with ASD have reduced age-related development, disabling them from reaching normal adult-levels of postural control (Kohen-Raz et al., 1992; Minshew et al., 2004). Children with ASD have demonstrated less stable and more variable postural control in the mediolateral direction (Kohen-Raz et al., 1992), which has been attributed to the insufficient ability to integrate visual, vestibular, and somatosensory inputs (Molloy, Dietrich, & Bhattacharya, 2003), and multiple sensory processing deficits (Lim et al., 2017).

Many previous studies that have examined postural control in children with ASD have investigated static posture, and few have focused on dynamic postural control. One such study examined postural control during gait initiation (Fournier et al., 2010). Gait initiation demands a deliberate destabilization of the center of mass (COM) and the ability to shift to a smaller base of support (BOS) to commence forward locomotion (Fournier et al., 2010). BOS has been defined as horizontal stride width during double limb support (Krebs, Goldvasser, Lockert, Portney, & Gill-Body, 2002), and it has been previously reported that individuals unconsciously widen their BOS due to unsteady gait (Nutt, Marsden, & Thompson, 1993). In the study by Fournier et al. (2010), children with ASD displaced their center of pressure 40% less during gait initiation and had less lateral center of pressure shifts, which could lead to the inability to separate their COM and center of pressure during gait initiation preventing efficient movement. The results of this study suggest there is impaired postural control, instability, or a distinct strategy for producing momentum in the mediolateral direction in children with ASD (Fournier et al., 2010). However, there have yet to be studies on dynamic postural control while walking in this population, which may provide insight as to whether stability is impaired while walking which could require a need for intervention.

Dynamic stability requires the combination of sensory and motor pathways from the central nervous system to coordinate the intended and actual movements (Fournier et al., 2010), while the COM moves away from the BOS. Margin of stability (MOS) is a measure of dynamic stability that has yet to be examined in children with ASD. MOS has been defined as the distance between the BOS and the extrapolated COM, considering COM position and velocity (Hof, AL et al., 2005). An individual may be dynamically stable if their extrapolated COM is within the

BOS, while the COM outside of the BOS may indicate instability (Sivakumaran, Schinkel-Ivy, Masani, & Mansfield, 2018). Quantification of MOS has been used to suggest when a control strategy, such as adjusting stride characteristics, may be used to prevent a fall and how close a fall may be to occurring (Bruijn, Meijer, Beek, & van Dieen, 2013).

Understanding how gait speed may play a role in dynamic stability has been widely investigated in healthy and clinical populations (Caderby, Yiou, Peyrot, Begon, & Dalleau, 2014; England & Granata, 2007; Fan, Li, Han, Lv, & Zhang, 2016; Lee, Bhatt, Smith-Ray, Wang, & Pai, 2019; Sivakumaran et al., 2018). Previous work has suggested that a slower walking speed is associated with greater stability in healthy adults (England & Granata, 2007), elderly, and neurologically impaired populations (Dingwell & Cusumano, 2000). Therefore, quantifying dynamic stability during different gait speeds may be of importance in children with ASD, whose gait velocity is typically slower than their neurotypical (NT) peers (Ambrosini et al., 1998; Nobile et al., 2011; Weiss et al., 2013) which may be a strategy to compensate for instability. The work done in Aim 1 of the study revealed that children with ASD demonstrate significant differences in lower extremity angular joint positions among different speeds, notably during the pre-swing sub-phase of gait and with the ankle playing a critical role in the kinematic strategy used to change speeds. Examining MOS will provide insight into whether children with ASD are more stable at their preferred velocity, and if the kinematic strategies used are a result of dynamic instability. The purpose of this study is to quantify dynamic stability using margins of stability in children with ASD at their preferred, fast, and slow speed. It is hypothesized that participants will demonstrate decreased stability during the fast and slow walking speed, as

children with ASD demonstrate differences in kinematic strategies during speeds that deviate from their preferred speed.

METHODS

Participants

An a priori power analysis (G*Power 3.1, Dusseldorf, Germany) was performed using data from (Nayate et al., 2012) to determine the appropriate sample size. Based on an effect size of 0.98, power of 0.8, and significance level of 0.05, it was determined a sample size of 14 would provide sufficient statistical power. A sample of 14 children, ages 8-17, with ASD participated in the current study. A clinical diagnosis of ASD was confirmed with documentation from a medical professional, or with an Individualized Education Program (IEP) for the child's school. All children were required to be free from any orthopedic condition which may further impact their ability to walk.

Instrumentation

Participants were instrumented bilaterally with spherical 14 mm retro-reflective markers, on the anterior superior iliac spines, posterior superior iliac spines, greater trochanters, iliac crests, medial and lateral femoral condyles, medial and lateral malleoli, and base of the second toe. Three-non-collinear reflective markers were placed bilaterally over the calcaneus. A single marker was placed on the sacrum for pelvis tracking. Thermo-plastic shells with four non-collinear marker clusters were secured on the lateral aspect, mid-segment of the thighs and legs using elastic wraps. Kinematic data was collected with a 10-camera three-dimensional motion capture system (200 Hz; Vicon Motion Systems, Ltd., Oxford, UK).

Protocol

First, anthropometric data, (height, mass, and leg length) were manually measured and recorded. Leg length was defined as the distance between the greater trochanter and the lateral malleolus (Sivakumaran et al., 2018). Participants walked over-ground at their preferred pace as kinematic data was collected and were reminded to walk as naturally as possible, when needed. The different speed conditions, fast and slow, were randomized among participants. In the fast speed condition, participants were asked to walk faster than their preferred speed and discouraged from running; any trials were discarded if the participant ran. For the slow speed condition, participants were instructed to walk slower than their preferred speed. Velocity was computed using time obtained from Brower Timing Gates (Brower Timing Systems, Draper, UT, USA) placed nine meters apart. Twelve motion capture trials were collected for each condition for a total of 36 trials, and participants were given breaks between conditions and if necessary.

Data Analysis

Raw kinematic data was exported to Visual 3D Biomechanical Software Suite (C-Motion, Inc., Germantown, MD, USA) for further analysis. Marker trajectories were smoothed using a low-pass Butterworth digital filter (6 Hz) to remove high frequency noise. A model was constructed from the smoothed marker trajectories including the pelvis and bilateral foot segments. Heel strike and toe-off events were identified using a velocity-based algorithm (Zeni Jr et al., 2008). MOS were identified at heel strike events. Horizontal and vertical center of mass (COM) position and velocity, were exported from Visual3D to calculate the extrapolated COM (XCOM), using equations from Hof et al. (2005).

$$XCOM = P_{COM} + \frac{V_{COM}}{\sqrt{g/l}}$$

P_{COM} and V_{COM} represent the horizontal position and velocity of the COM, respectively, and g represents the gravitational constant, and l represents the leg length multiplied by 1.2 (Hof, AL et al., 2005). The base of support (BOS) boundaries were identified as the medial/lateral BOS (BOS_{ML}) and anterior/posterior BOS (BOS_{AP}). BOS_{ML} was the lateral aspect of the leading foot and BOS_{AP} was the position of the toe on the leading foot. BOS_{ML} and BOS_{AP} were exported from Visual3D. Each MOS was calculated with the XCOM and BOS obtained using the following equation established from Hof et al. (2005).

$$MOS = BOS - XCOM$$

Participant stride characteristics, including stride width, bilateral step length, and double limb support time were also calculated in Visual3D to further understand, what strategies, if any, children with ASD are adapting to preserve their stability in response to different speeds.

Statistical Analysis

Analysis of variances (ANOVAs) with repeated measures were conducted on each of the margins of stability to test for significant differences among the three speeds (α=0.05). If significance was detected, the Sidak adjustment was used for pairwise comparisons. Additionally, repeated measures ANOVAs were conducted on stride width, step length, and double limb support time to test for significant differences among speeds (α=0.05). Right and left step length was collapsed as there were no significant differences between right and left step length (p=0.71). The assumption of sphericity was tested with Maulky's test for sphericity for all tests, and if the assumption of sphericity was violated, the Greenhouse-Geisser estimate was used. Effect sizes were calculated as partial eta squared (η^2) and interpreted with Cohen's scale (Cohen, 1988).

RESULTS

Participant Anthropometrics and Gait Velocity

Participant anthropometric data, including leg length is included (**Table 3.1**). Participants with ASD had an average gait velocity of 1.06 ± 0.13 m/s for the preferred condition, 1.41 ± 0.16 m/s for the fast condition, and 0.72 ± 0.16 m/s for the slow condition.

Table 3.1 Participant Anthropometrics

	Sex	Age	Height (m)	Mass (kg)	Leg Length (m)
ASD n=14	2 F, 12 M	11.64 ± 2.13	1.55 ± 0.15	54.40 ± 20.16	0.74 ± 0.08

Mean and (±) standard deviation values for participant anthropometric data

Margins of Stability

Participants with ASD did not have significant differences in MOS_{ML} ($F_{(2,26)} = 0.43$, $p=0.43$, $\eta^2=0.06$) or in MOS_{AP} ($F_{(2,26)} = 0.71$, $p=0.50$, $\eta^2=0.05$) among speed conditions. (**Table 3.2**)

Table 3.2 Mean Margins of Stability Among Speed Conditions

	Preferred	Fast	Slow
MOS_{ML}	0.64 ± 0.44	-0.40 ± 2.11	0.10 ± 3.45
MOS_{AP}	1.56 ± 13.58	-1.64 ± 9.40	2.75 ± 8.39

Mean and (±) standard deviation values for Margins of Stability (MOS) for each condition. MOS_{ML}: Medial/Lateral MOS, MOS_{AP}: Anterior/Posterior MOS. Data are measured in

centimeters. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions.

Stride Characteristics

Analysis revealed significant differences in stride width among speed conditions ($F_{(2,26)} = 4.04$, p=0.03, η^2=0.29) ;however, there were no pairwise comparisons revealed. Step length was statistically different among conditions, ($F_{(1.32,13.16)} = 21.58$, p<0.001, η^2=0.68), and pairwise comparisons were observed between each condition comparison (preferred and fast p=0.01; preferred and slow p=0.01 ; fast and slow p<0.001). Additionally, double limb support time was significantly different among speeds ($F_{(1.10,11.00)} = 60.0$, p<0.001, η^2= 0.86), with significant pairwise comparisons between each of the conditions (p<0.001 for all comparisons). (**Table 3.3**)

Table 3.3. Stride Characteristics Among Speed Conditions

	Preferred	**Fast**	**Slow**	***p* value**
Stride Width (cm)	11.91 ± 2.52	11.14 ± 3.15	12.58 ± 2.88	0.03 *
Step Length (cm)	53.72 ± 15.28	61.0 ± 19.41	46.59 ± 14.27	<0.001 ✦•♦
Double Limb Support Time (s)	0.17 ± 0.07	0.08 ± 0.05	0.33 ± 0.12	<0.001 ✦•♦

Mean and (±) standard deviation values for spatial temporal variables during each condition. Asterisk (*) indicates a statistically significant (p<0.05) difference among the conditions in the F-test, (♦) indicates a statistically significant difference between preferred and slow, (✦) indicates a statistically significant difference between preferred and fast, (•) indicates statistically significant difference between slow and fast.

DISCUSSION

The purpose of the current study was to quantify dynamic stability using margins of stability in children with ASD at their preferred, fast, and slow speed. The hypothesis that children with ASD would demonstrate decreased stability during the fast and slow walking speed was not supported, as there were no significant differences among the speed conditions. The lack of significant differences among the three speeds may suggest that children with ASD do not have any differences in their overall dynamic stability with a change in gait speed. While not significantly different from other conditions, the fast speed revealed negative values for MOS_{ML} and MOS_{AP}, indicating their XCOM was outside the BOS and instability may have been present, but not enough to elicit a significant difference from the other conditions. Additionally, children with ASD demonstrated significant differences in stride width, step length, and double limb support time among speeds, which are adaptations expected as an individual changes their gait speed. However, these changes may not be enough to alter dynamic stability in different speed conditions for children with ASD. This may be advantageous for children with ASD, as walking faster and slower could be typical daily tasks, and dynamic stability remains relatively unchanged when altering their gait speed from their preferred pace.

An individual can change the size of their BOS by modifying their stride characteristics, which may depend on the motion of the COM (Young & Dingwell, 2012). If children with ASD were able to modify their BOS in response to different gait speeds, it may suggest that they are appropriately adjusting step placement and stride timing to help to preserve mechanical stability (Sivakumaran et al., 2018; Young & Dingwell, 2012). The findings of the current study are inconsistent with previous literature (Sivakumaran et al., 2018; Young & Dingwell, 2012), which

revealed changing step length altered MOS_{AP} and changing stride width altered MOS_{ML} and MOS_{AP}. This could be due to previous studies focusing on healthy adults, rather than children. Additionally, previous studies have involved participants walking on treadmills. Treadmill walking is less variable than overground walking (Hollman et al., 2016) and mechanically controls participants' speeds. Overground walking in the current study demonstrated large variation among subjects with ASD, which was revealed by large standard deviation values, especially for the MOS_{AP} values. The large variation in the MOS values among study participants may also be explained by the heterogenous walking pattern that has been observed in the ASD population (Dufek et al., 2017; Eggleston et al., 2017). However, the work done in the current study was aimed at identifying dynamic stability, and group trends in postural instability have been previously established in this population (Fournier et al., 2010; Kohen-Raz et al., 1992; Minshew et al., 2004).

In addition to changing stride characteristics, to accommodate different speeds, children with ASD may be preserving their stability by adjusting the position or velocity of their COM (Sivakumaran et al., 2018). While not significant, children with ASD displayed decreased MOS_{AP} values in response to the fast speed and increased in response to the slow speed. Previous research has suggested that a decrease in MOS indicates the COM is closer to the boundaries of the BOS, while an increase in MOS indicates the COM is further inside the BOS boundaries (Peebles, Reinholdt, Bruetsch, Lynch, & Huisinga, 2016). Additionally, previous research has suggested that a slower walking velocity leads to an increase in stability (England & Granata, 2007), and children with ASD tend to display a slower walking velocity than neurotypical children (Ambrosini et al., 1998; Nobile et al., 2011; Weiss et al., 2013). However, when

children with ASD walk slower as they do in this study, they do not appear to be more stable. The adaptations children with ASD made to achieve a faster or slower gait speed may be considered “conservative gait strategies”, which could be used as a means to reduce forward COM movement outside their BOS and to decrease time balancing on a single limb (Maki, 1997; Peebles et al., 2016).

The current study examined MOS at heel strikes for children with ASD, due to many studies quantifying stability during double limb support (Hof, AL et al., 2005; Hof, At L., van Bockel, Schoppen, & Postema, 2007; Young & Dingwell, 2012). However, it may be possible that single limb support may contribute more to the overall postural instability that is observed in this population. Future studies should examine MOS during single limb support during different speeds to determine any significant differences for children with ASD.

Limitations

The current study has limitations including not controlling for cognitive or mental abilities within the sample. It has been suggested that comorbidities of cognitive impairment may play a role in postural stability and could lead to increase instability (Kohen-Raz et al., 1992). Future studies may examine MOS in a group of participants with ASD with various levels of cognitive impairment. Another possible limitation of the current study is that children were expected to perform fairly short bouts of overground walking in the laboratory, as opposed to a treadmill which may capture a much higher number of steps. By examining a longer duration of walking, the differences in MOS among preferred, fast, and slow walking speeds may be more apparent than the current study.

CONCLUSION

In summary, the purpose of the current study was to quantify dynamic stability by means of MOS in children with ASD in different walking speeds. The findings revealed that children with ASD do not demonstrate significantly different MOS in the medial/lateral direction or the anterior/posterior direction among preferred, fast, or slow walking speeds. However, children with ASD modified stride width, step length, and double limb support time among speeds, which indicates they were able to adjust their BOS and maintain their COM within the BOS boundaries. This may prove beneficial for children with ASD, as increasing and decreasing their walking speed is a part of daily life and dynamic stability appears consistent among different speed conditions. The current study demonstrated large variations in MOS_{ML} and MOS_{AP}, which may reflect the heterogenous nature of gait in the ASD population. Future studies may consider evaluating MOS at the single subject level to determine if certain children have altered MOS among different speeds, which is not being reflected at the group level. However, children with ASD may be using conservative gait strategies to maintain their dynamic stability while walking in different speeds, and the postural instability observed in this population may be limited to static posture.

CHAPTER 4: CHILDREN WITH AUTISM DO NOT EMPLOY COGNITIVE ABILITIES IN ALTERING GAIT SPEED

INTRODUCTION

Research has determined that children with Autism Spectrum Disorder (ASD) present behavioral symptomology (American Psychiatric Association, 2013) and significant motor impairments (McPhillips, Finlay, Bejerot, & Hanley, 2014) in gross motor development and locomotor skills (Pan et al., 2009) compared to age-matched neurotypical (NT) children. The majority of children with ASD have scored lower on motor skill assessments that include gross and fine motor coordination (Dyck et al., 2004) and the movement assessment battery for children (Green et al., 2009). In addition to behavioral symptoms and identified motor deficits, cognitive abilities are also impacted in children with ASD (Brunsdon et al., 2015; Kas et al., 2014; Maenner et al., 2020). Research has established that children with ASD perform worse in cognitive tasks compared to NT controls, with about one third of ASD individuals presenting with more than one cognitive impairment (Brunsdon et al., 2015). Three cognitive specific domains affected in individuals with ASD are executive function, perception, and attention (Kas et al., 2014). There are conflicting views as to whether cognitive impairments may be a fundamental aspect of ASD, with some arguing that it may be one of many symptoms but not present in every child (Brunsdon et al., 2015). However, other research suggests that deficits in executive functions and perceptual abilities may explain the observed impairments in social skills in individuals with ASD (Rajendran & Mitchell, 2007).

Various research has identified impairments of executive functions and implied that these deficits could be a core symptom of ASD (Dichter et al., 2010). Past research shows that children with ASD demonstrate decreased executive functioning including impairments of working memory, planning, (Joseph, McGrath, & Tager-Flusberg, 2005), and inhibition (Narzisi, Muratori, Calderoni, Fabbro, & Urgesi, 2013). Other results of executive functioning assessments have shown that children with ASD tend to make perseverative errors, which may indicate a lack of behavioral flexibility or impairments in reversal learning (Dichter et al., 2010). Furthermore, adults with ASD have also shown cognitive deficits including impaired executive functions, in areas such as signal detection, response inhibition, motor coordination, and planning (Lai et al., 2012). It is crucial to note that executive functions have been suggested as playing a role in motor performance, particularly in those with neurological impairments (Fournier et al., 2010). Secondly, individuals with ASD have displayed abnormalities with perception (Cook, 2016), in areas such as time perception (Falter, Noreika, Wearden, & Bailey, 2012) and multisensory processing (Donohue, Darling, & Mitroff, 2012), which both involve connectivity of the long range brain networks. Further, individuals with ASD have demonstrated differences in sensory processing (Boucher, 2008), particularly they have performed worse on tasks which require global processing (Brunsdon et al., 2015). Lastly, there is a body of evidence indicating attentional deficits in individuals with ASD (Kas et al., 2014), attributed to aberrations of processing in frontal brain areas (Belmonte & Yurgelun-Todd, 2003). The divided attention (Sinzig, Bruning, Morsch, & Lehmkuhl, 2008) and sustained attention processes have appeared specifically compromised (Johnson et al., 2007). Moreover, children with ASD have demonstrated decreased performance in assessments evaluating auditory attention (Narzisi et al., 2013).

Previous studies have examined the relationships between cognitive state and the ability to alter gait speed, and suggested that greater cognitive resources may be required to walk faster than an individual's preferred walking speed to maintain balance and adapt to changing surroundings (Callisaya, Michele L. et al., 2017). Past studies have determined that a slower speed in fast walking is associated with decreased overall cognition (Deshpande et al., 2009; Fitzpatrick et al., 2007). Walking speed reserve has been defined as the ability to change from preferred to fast walking speed (Middleton et al., 2016). A past study by Callisaya et al. (2017) on elderly individuals found that worse cognitive impairment was associated with a poorer ability to increase speed and walk quickly. Therefore, greater cognitive abilities may be linked to a greater walking speed reserve (Callisaya, ML et al., 2012). These findings may be relevant for children with ASD, who often have associated cognitive impairments and motor deficits. There have been few studies that have examined the potential relationship between cognitive abilities and gait mechanics in this population. It is worth investigating whether the level of the cognitive abilities impacts the capability to change gait speed in children with ASD, similarly to those with decreased cognition. Additionally, Aim 1 of the project identified kinematic differences within children with ASD when altering gait speed, which was not due to differences in dynamic stability as exhibited in Aim 2. Therefore, the kinematic differences observed may be due to cognitive resources that affect how children with ASD are changing their walking speed. The purpose of the current study is to examine the relationships between cognitive abilities and the ability to increase walking speed in children with ASD and compare to NT children. It is hypothesized that children with ASD will present decreased cognitive abilities than NT children, and those with reduced processing speed, attention, and executive functions will have a slower walking speed, lower walking speed reserve, and different kinematic strategies.

METHODS

Participants

An a priori power analysis (G*Power 3.1, Dusseldorf, Germany) was performed using data from (Nayate et al., 2012) to determine the appropriate sample size. Based on an effect size of 0.98, power of 0.8, and significance level of 0.05, it was determined a sample size of 14 participants for each group would provide sufficient statistical power. The study included 14 children with ASD and 14 age-and-sex matched neurotypical (NT) children between the ages of 8-17. A clinical diagnosis of ASD was confirmed with documentation from a medical professional, or with an Individualized Education Program (IEP) for the child's school. All NT participants were required to be free from any neurological impairments. All children were required to be free from any orthopedic condition/disorder which may affect their ability to walk.

Instrumentation

Executive function, attention, and processing speed assessments from the Cognitive Battery of the NIH Toolbox for Assessment of Neurological and Behavioral Function (App Version 1.23.4300) were administered on an iPad (Apple Inc., Cupertino, CA, USA). Participants were instrumented with spherical 14 mm retro-reflective markers on the anterior superior iliac spines, posterior superior iliac spines, greater trochanters, iliac crests, medial and lateral femoral condyles, medial and lateral malleoli, and base of the second toe, bilaterally. Three-non-collinear reflective markers will be placed bilaterally over the calcaneus. A single marker will be placed on the sacrum for pelvis tracking. Additionally, thermo-plastic shells with four non-collinear marker clusters will be placed on the lateral aspect, mid-segment of the thighs and legs using elastic wraps. Kinematic data will be collected with a 10-camera three-dimensional motion

capture system (200 Hz; Vicon Motion Systems, Ltd., Oxford, UK). Participants completed all study-related activities in one laboratory session.

Protocol

To evaluate cognitive abilities, (*i.e.*, processing speed, attention, and executive functions) participants performed three tasks, respectively: Pattern Comparison Processing Speed Test, Flanker Inhibitory Control and Attention Test, and the Dimensional Change Card Sort Test. Two versions of tests were implemented to accommodate for age, with one version standardized for ages 8-11 and the other for 12-17. First, participant demographic information was collected. The assessment contained standardized instructions and began with a brief training period to ensure the participant understood the instructions. Upon completion of the cognitive testing, the participants began the gait analysis portion of the study. Participants began by walking over-ground at their preferred speed and reminded to walk as naturally as possible, if needed. In the fast speed condition, participants were instructed to walk faster than their preferred speed and discouraged from running. Trials were discarded if a participant ran. In the slow speed condition, participants were asked to walk slower than their preferred speed. The two experimental conditions were be randomized among participants. Timing was monitored using Brower Timing Gates (Brower Timing Systems, Draper, UT, USA) placed nine meters apart. Twelve motion capture trials were collected for each condition for a total of 36 trials, and participants were given breaks when necessary.

Data Analysis

Cognitive Assessments: Several scores can be obtained for the tests included in the Cognitive Battery of NIH Toolbox. The computed scores, which accounts for accuracy and timing, will be

used to compare scores in each assessment between ASD and NT groups. Reaction time and accuracy will also be analyzed separately for each assessment and compared between groups. The calculated age-corrected standard score, which is a standardized score based on comparisons of scores to those of the same age, will be utilized for analysis with gait variables.

Gait Variable Analysis: Raw kinematic data was exported to Visual 3D Biomechanical Software Suite (C-Motion, Inc., Germantown, MD, USA) for further analysis. Marker trajectories were smoothed using a low-pass Butterworth digital filter (6 Hz) to remove high frequency noise. A seven-segment model was constructed from the smoothed marker trajectories including the pelvis and bilateral thigh, leg, and foot segments. All data were normalized to 100% of the gait cycle (101 data points). Heel strike and toe-off events were identified using a velocity-based algorithm (Zeni Jr et al., 2008). The gait cycle was divided into seven sub-phases (Rancho Los Amigos National Rehabilitation Center, 2001) as a percentage of the gait cycle; the current study focused on pre-swing (PSw; 51–60% of the gait cycle) sub-phase. The gait variables of interest included the bilateral knee and ankle joint positions during PSw, as this sub-phase demonstrated differences in each lower extremity joint and knee and ankle angular joint positions had the highest effect sizes from Aim 1. Walking speed reserve (WSR) was calculated as the difference between the fast and preferred speed (Fast Speed – Preferred Speed) (Callisaya, Michele L. et al., 2017). Gait velocities were obtained from time collected from timing gates.

Statistical Analysis

For cognitive assessment scores, tests of normal distribution were conducted using the one-sample Kolmogorov-Smirnov test. If the scores followed a normal distribution, independent

sample t-tests (α=0.05) were conducted to test for significant differences between groups. If scores did not follow a normal distribution, the Mann-Whitney U test was used for comparisons between groups (α=0.05). Two-way Analysis of variances (ANOVAs) with repeated measures were used to identify group and test main effects, and to determine a group x test interaction (α=0.05). These analyses used the age-corrected standardized scores for each group.

An ANOVA with repeated measures was used to determine if there were significant group or condition main effect between gait velocity during the preferred, fast, and slow conditions. An independent sample t-test (α=0.05) was conducted on the WSR to determine if there was a significant difference between the two groups. Two-way ANOVAs with repeated measures were used to identify group and speed main effects, and to determine whether a group x speed interaction (α=0.05) between bilateral knee and ankle angular joint positions at each speed existed.

The correlation between scores on cognitive assessments and gait velocities, walking speed reserve, and lower extremity angular joint positions were assessed using Pearson's correlation coefficient (r) for normally distributed data, and Spearman's correlation coefficient (rho) was used for nonparametric data correlations. A significant correlation was assumed for $p<0.05$.

RESULTS

Demographic Information

The results of participant demographic data for the current study are listed, including sex, age, height, mass, dominant hand, race, and highest grade level completed for each group (**Table 4.1**). One participant from the NT group was removed from analysis, as they were an outlier for low performance on cognitive assessments, making the total for the NT group 13 participants.

Table 4.1 Participant Demographics

	ASD (n=14)	**NT (n=13)**
Sex (male)	12	11
Age (years**)**	11.64 ± 2.13	11.23 ± 2.05
Height (m**)**	1.55 ± 0.15	1.54 ± 0.13
Mass (kg**)**	54.40 ± 20.16	55.98 ± 25.27
Dominant Hand (right**)**	11	12
Race		
White	13	8
Other	1	5
Hispanic	14	11
Highest Grade Level Completed	5.07 ± 2.16	5.15 ± 2.03

Mean and (±) standard deviation values for participant demographic data

Cognitive Assessments

The analysis revealed significant differences between groups in all three cognitive assessments. In the Pattern Comparison Processing Speed Test, there was a significant difference in computed

score (t(25)= -2.62; p=0.01), accuracy (t(25)= -2.60; p =0.01), and reaction time (U= 39.00; p=0.01) between the ASD and NT groups. For the Flanker Inhibitory Control and Attention Test, there was a significant difference in the computed score (U= 19.00; p<0.001) and reaction time (U= 19.00; p<0.001), but not in the accuracy (U= 71.50; p= 0.08) between groups. Lastly, for the Dimensional Change Card Sort Test, there was a significant difference between ASD and NT groups in computed score (t(25)= -3.28; p=0.002), accuracy (U = 50.00; p=0.04), and reaction time (t(25)= -3.324; p<0.001) (**Table 4.2**). Analysis of age-corrected standardized scores did not reveal a significant group x test interaction ($F_{(2,50)}$=0.75, p=0.42, η^2= 0.03); however, there was a significant group main effect ($F_{(1,25)}$=18.24, p< 0.001, η^2= 0.42,) and a significant test main effect ($F_{(2,50)}$=11.30, p=0.001, η^2= 0.31).

Table 4.2 ASD and NT Group Cognitive Scores

	ASD (n=14)	**NT (n=13)**
Pattern Comparison Processing Speed Test		
Computed Score *	46.64 ± 13.01	59.23 ± 11.85
Accuracy *	38.29 ± 8.16	46.0 ± 7.21
Reaction Time *	2.00 ± 0.76	1.50 ± 0.34
Age-Corrected Score *	87.86 ± 19.86	111.0 ± 20.61
Flanker Inhibitory Control and Attention Test		
Computed Score *	6.60 ± 1.15	8.01 ± 0.37
Accuracy	4.91 ± 0.27	5.0 ± 0.0
Reaction Time *	1.69 ± 0.98	3.01 ± 0.37
Age-Corrected Score *	75.71 ± 12.00	91.92 ± 12.22
Dimensional Change Card Sort Test		
Computed Score *	6.40 ± 1.23	7.60 ± 0.52

Accuracy *	5.85 ± 0.38	6.11 ± 0.13
Reaction Time *	0.73 ± 0.57	1.50 ± 0.52
Age-Corrected Score *	82.93 ± 11.93	99.08 ± 9.30

Mean and (±) standard deviation values for each cognitive assessment. Asterisk (*) indicates a statistically significant (p<0.05) difference between groups

Gait Variable Analysis

Analysis revealed a condition main effect ($F_{(2,50)}$=276.11, p<0.001, η^2= 0.92); however, there was no significant group main effect ($F_{(1,25)}$=4.22, p= 0.06, η^2= 0.14) or significant group x condition interaction ($F_{(2,50)}$=0.002, p=0.99, η^2= 0.001). There was also no significant difference in WSR between groups (t(25)= -0.08; p=0.94) (**Figure 4.1**). Analysis of bilateral knee and ankle angular positions revealed a significant speed main effect for each joint (Right knee: $F_{(1.53,38.21)}$=78.2, p<0.001, η^2= 0.76; Left Knee: $F_{(1.52,37.91)}$=70.10, p<0.001, η^2= 0.74; Right Ankle: $F_{(2,50)}$=110.31, p<0.001, η^2= 0.82; Left Ankle: $F_{(1.55,38.77)}$=88.71, p<0.001, η^2= 0.78). All pairwise comparisons were significant (p<0.001). However, the main effect of group for all analyzed bilateral knee and ankle angular positions was not significant (Right knee: $F_{(1,25)}$=1.73, p=0.20, η^2=0.07; Left Knee: $F_{(1,25)}$=2.32, p=0.14, η^2= 0.09; Right Ankle: $F_{(1,25)}$=1.57, p=0.22, η^2= 0.06; Left Ankle: $F_{(1,25)}$=1.31, p=0.26, η^2= 0.05). Similarly, the group x speed interaction was not significant (Right knee: $F_{(1.53,38.21)}$=0.01, p=0.97, η^2<0.001; Left Knee: $F_{(1.52,37.91)}$=0.31, p=0.68, η^2= 0.01; Right Ankle: $F_{(2,50)}$=0.78, p=0.47, η^2= 0.03; Left Ankle: $F_{(1.55,38.77)}$=1.45, p=0.25, η^2= 0.06). (**Figures 4.2-4.5**)

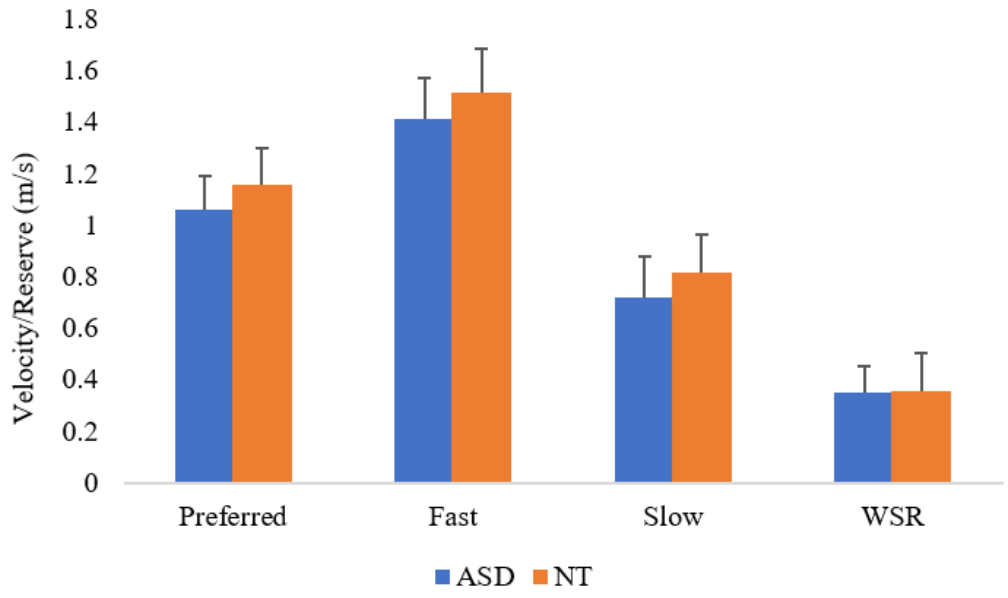

Figure 4.1. Mean and standard deviation for velocities during the preferred, fast, and slow conditions and walking speed reserve for each group. Asterisk (*) indicates a statistically significant (p<0.05) difference between groups. (WSR: Walking Speed Reserve)

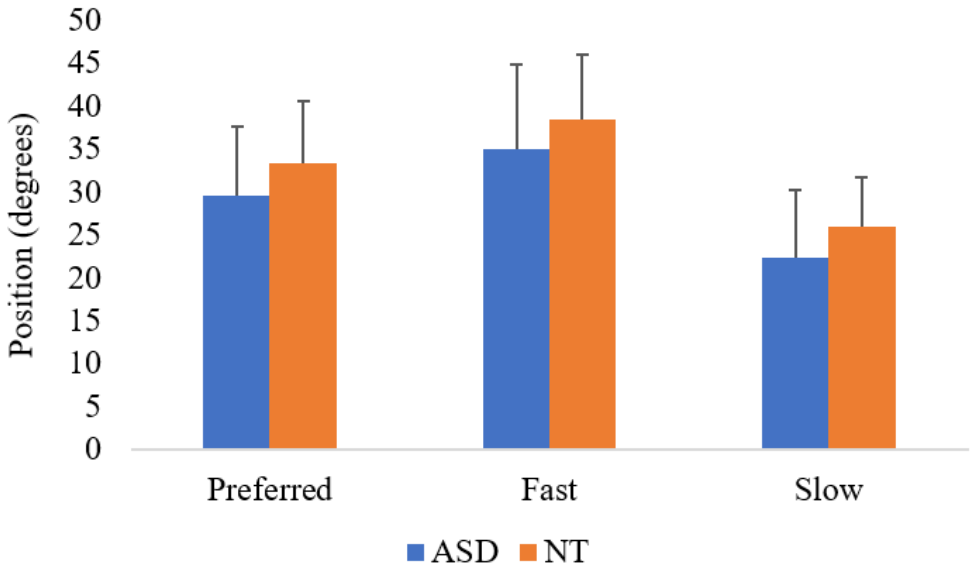

Figure 4.2 Mean and standard deviation for right knee angles for the preferred, fast, and slow conditions during PSw sub-phase for each group. Positive values indicate flexion. Significant main effect of speed was revealed.

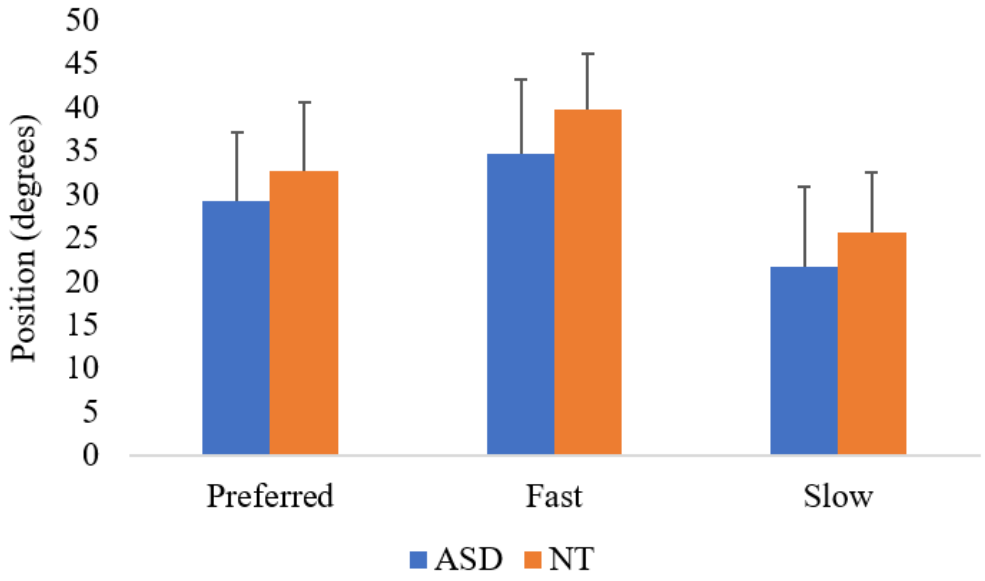

Figure 4.3 Mean and standard deviation for left knee angles for the preferred, fast, and slow conditions during PSw sub-phase for each group. Positive values indicate flexion. Significant main effect of speed was revealed.

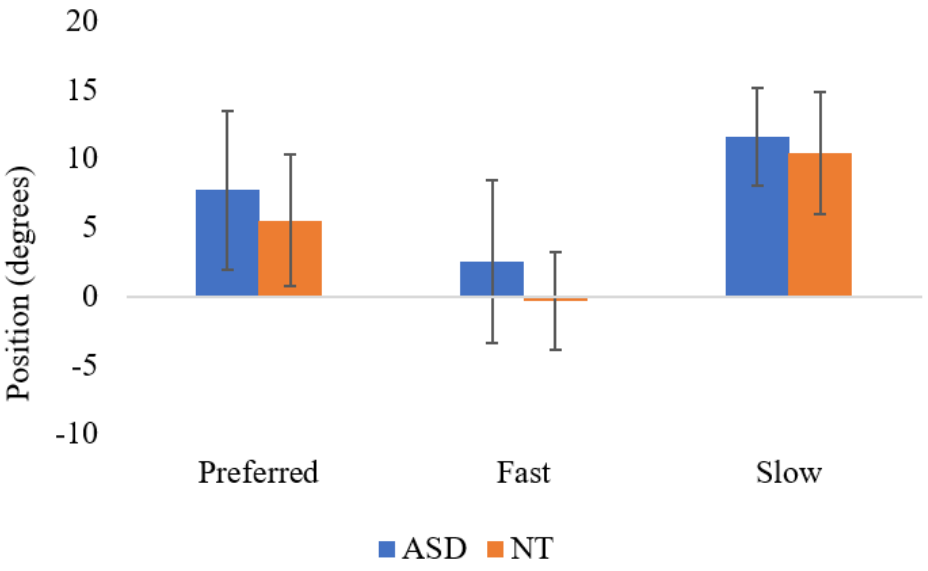

Figure 4.4 Mean and standard deviation for right ankle angles for the preferred, fast, and slow conditions during PSw sub-phase for each group. Positive values indicate dorsiflexion. Significant main effect of speed was revealed.

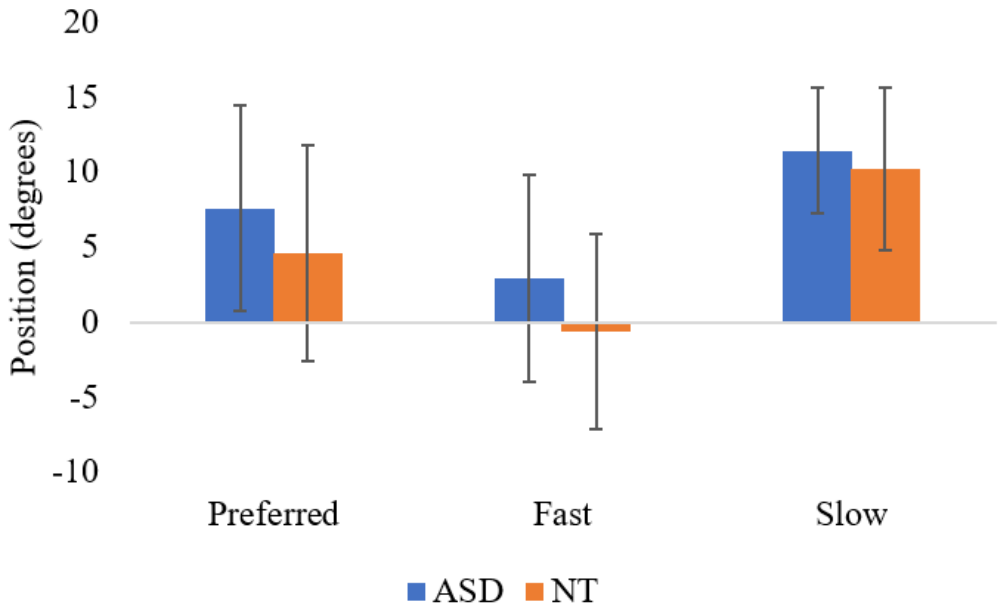

Figure 4.5 Mean and standard deviation for left ankle angles for the preferred, fast, and slow conditions during PSw sub-phase for each group. Positive values indicate dorsiflexion. Significant main effect of speed was revealed.

Correlations Among Cognitive Abilities and Gait Variables

A total of 100 correlations were analyzed to determine if significant correlations were observed between cognitive scores, walking velocity in each condition, WSR, and PSw bilateral knee and ankle angular joint positions. Significant correlations are included in **Table 4.3**.

Table 4.3 Cognitive and Gait Variable Correlations

	Dimensional Change Card Sort Test		Flanker Inhibitory Control and Attention Test	
	Age-Corrected Standard Score	Reaction Time	Age-Corrected Standard Score	Reaction Time
ASD				
P: Left Knee	0.59; p=0.03			
NT				
P: Velocity		0.62; p=0.02		
F: Velocity	0.6; p=0.03			
S: Velocity		0.59; p=0.04		
P: Right knee	0.56; p=0.04			
F: Right knee	0.56; p=0.04			
F: Left Knee	0.63; p=0.02		0.63; p=0.02	
S: Left Knee	0.59; p=0.03		0.62; p=0.02	
F: Right Ankle	-0.57; p=0.04		-0.86; p<0.001	

Pearson's Correlation Coefficient (r) and p values for each significant ($p<0.05$) correlation. (P: Preferred Condition, F: Fast Condition, S: Slow Condition)

DISCUSSION

The purpose of the current study was to examine the relationships between cognitive abilities and the ability to increase walking speed in children with ASD and compare to NT children. The hypothesis that children with ASD would present with decreased cognitive abilities in areas of perception, attention, and executive function was supported, as mostly all computed scores, accuracy, and reaction time scores were significantly different between groups. Children with ASD had decreased performance compared to NT children in all three cognitive domains examined in the current study. However, children with ASD and NT did not demonstrate any

significant differences in gait velocities in each of the conditions, WSR, or angular joint positions in the knee and ankle. Upon examination of significant correlations between cognitive assessment scores and gait variables, the ASD group had only one significant correlation between left knee flexion and score on the Dimensional Change Card Sort Test. The NT group had several significant correlations, notably between scores and reaction time in the Dimensional Change Card Sort test and knee flexion, ankle dorsiflexion, and gait velocity in each condition. These findings may suggest that children with NT development may employ some executive function processes to change their gait speed, while children with ASD do not utilize these processes.

Children with ASD present with reduced (slower and/or less accurate) cognitive processing in areas of attention, processing speed, and executive function, (Kas et al., 2014), which is further confirmed in this study. However, the lack of significant correlations between cognitive abilities and gait, is inconsistent with past literature, which suggested that cognitive impairments have a negative effect on gait performance (Sheridan & Hausdorff, 2007). The absence of significant correlations between cognitive abilities, in particular, executive functions, and gait variables in changing gait speed in children with ASD may indicate that they do not utilize executive functions, attention, or processing when changing their walking speed. This may be possible because their reduced cognitive abilities and slower cognitive processing does not allow them to utilize those resources to assist them in changing gait speed. It may also be possible that prioritization was given primarily to gait and the task of either walking slower or faster. Additionally, children with ASD did not show differences in walking velocity or kinematic

strategies in any of the conditions or in WSR when compared to the NT group in the current study. This suggests that children with ASD are able to mechanically alter their gait speed similarly to those with NT. As observed in Aim 1, children with ASD exhibit different kinematic strategies in each gait speed; however, those strategies may not be related to their cognitive abilities in executive function and attention domains, while NT children may utilize those processes to achieve different kinematic strategies in each of the three speeds.

The presence of significant correlations between cognitive abilities and gait parameters used to change gait speed in children with NT development may indicate that children use executive function processes to change their walking speed. Executive function involves higher cognitive processes that use information to adjust and produce behavior, which involves initiation or intention of action, planning, and working memory (Lezak, Howieson, Loring, & Fischer, 2004). These cognitive and mobility relationships have been identified in other populations, including healthy adults with normal cognitive abilities (Hausdorff, Yogev, Springer, Simon, & Giladi, 2005; Persad, Jones, Ashton-Miller, Alexander, & Giordani, 2008; Yogev-Seligmann, Hausdorff, & Giladi, 2008). Past studies suggest that executive function plays a role in several balance and walking tasks (Hausdorff et al., 2005). In addition to executive function, children with NT development demonstrated multiple significant correlations between attention and kinematic strategies in this study. This is consistent with previous literature that suggests attention plays a role in gait, even in healthy adults who are cognitively high functioning with no gait impairments (Yogev-Seligmann et al., 2008). The findings from the current study and past studies further

supports that gait may not be purely an automatic activity but requires some amount of higher-level cognitive input (Yogev-Seligmann et al., 2008).

Previous research suggests the relationship between cognitive abilities and gait is more apparent in complex environmental conditions or locomotor tasks (Persad et al., 2008; Yogev-Seligmann et al., 2008). Additional use of attention and executive function resources are required for changes in walking surface (Sheridan & Hausdorff, 2007), obstacle avoidance (Ble et al., 2005), or dual task situations (Holtzer, Verghese, Xue, & Lipton, 2006). In the current study, participants were asked to walk faster or slower than their preferred pace. Research suggests that goal-oriented movement with intention involves some degree of cognitive resources (Sheridan & Hausdorff, 2007). However, the lack of significant correlations between cognition and gait parameters in the ASD group may indicate that the task of walking at a preferred, fast, or slow speed was not cognitively demanding enough for cognitive resources to affect gait performance. This may be due to fast and slow walking being everyday tasks that could be a more common motor skill for which the individuals with ASD developed distinct strategies from NT children. It is possible that more demanding motor tasks or dual tasking would make the relationships between cognitive abilities and changing gait speed more visible, particularly in the ASD group.

Past studies have focused on older adults with neurological conditions, such as Alzheimer's (Sheridan & Hausdorff, 2007) and dementia (Callisaya, Michele L. et al., 2017), which may account for the inconsistent findings observed in the current study. Age could play a role in gait

decline, as well as cognitive decline in the ASD population. Past studies have established that adults with ASD present with slower reaction times, slower gait speed, and decreased step and stride times (Morrison et al., 2018). Future studies may examine adults with ASD to determine if there are more apparent relationships between cognitive abilities and changing gait speed. Additionally, many studies in this area utilize a dual task paradigm to investigate the effects of a concurrent task on gait parameters. Future research may focus on this phenomenon, and how children with ASD perform in cognitive and walking tasks when cognitive resources may be divided. Lastly, examining relationships between cognitive abilities and walking while changing walking surfaces may be worth examining in children with ASD, as changes in incoming sensory information during gait have shown decreased gait performance and children with ASD typically present with deficits in sensory processing (Boucher, 2008).

Limitations

The current study has limitations, including a small sample size. The sample size may make it difficult to generalize the lack of significant correlations between cognitive abilities and gait parameters in the ASD group, and the presence of significant correlations in the NT group. Future studies should include a larger sample size to see if similar results are still observed. Additionally, participants performed overground walking over a short distance for each trial, and because the trials were short, cognitive resources may not have had a chance to be utilized in the ASD group, as they exhibited slower cognitive processing. By performing walking on a treadmill, where more steps could be captured for a longer duration of time, the relationship between cognitive abilities and gait speed may be more apparent. Lastly, co-morbidities, such as attention deficit hyperactivity disorder, were not controlled for within the ASD sample collected.

This may have influenced the scores on the cognitive assessments, and future studies may aim to account for these differences.

CONCLUSION

In conclusion, this study aimed to determine if there was a potential relationship between cognitive abilities and gait variables involved in changing gait speed in children with ASD. When compared to NT children, children with ASD demonstrate reduced cognitive abilities and slower cognitive processing in areas of executive function, attention, and processing speed. However, the groups did not demonstrate differences in walking velocity, WSR, or in lower extremity kinematic strategies when changing gait speed. Additionally, children with ASD do not demonstrate any significant correlations between cognitive assessment scores and gait variables, while NT children demonstrate relationships primarily in executive function and gait variables. This may indicate that children with ASD are not using cognitive resources to change their speed while NT children do, possibly due to their limited cognitive abilities. This could be advantageous for children with ASD, as decreased cognitive abilities and slower cognitive processing may not impact daily walking tasks and locomotion. However, based on the findings in the NT group, the involvement of cognitive resources in changing gait speed is an important component of the motor control. Future studies should examine dual task conditions, which demand higher cognitive resources to determine if a more visible relationship exists between changing gait speed and cognitive abilities in children with ASD.

CHAPTER 5: GENERAL DISCUSSION

Recent research has suggested that ASD is manifests as a movement disorder with motor and locomotion deficits. It is essential to understand how children with ASD are performing in various gait tasks, including changing their walking speed, and how their cognitive abilities may play a role in locomotion. The first aim of the project was to examine the kinematic strategies used by children with ASD in three speeds (preferred, fast, and slow). The second aim was to quantify dynamic stability in children with ASD in all three speeds. The third aim was to examine the relationships between cognitive abilities and the ability to increase walking speed in children with ASD.

The second chapter of this dissertation revealed that children with ASD present with significantly different bilateral hip, knee, and ankle angular joint positions at different gait sub-phases. Particularly, the PSw sub-phase revealed differences in all the lower extremity joints. At PSw, children with ASD demonstrated increased hip extension, increased knee flexion, and decreased dorsiflexion at increased speeds. The largest effect sizes observed throughout this study were the bilateral ankle angular joint positions, indicating that the ankle may be the primary strategy used in children with ASD to change their gait speed. Decreased dorsiflexion of the ankle may provide support and aid with propulsion when changing gait speed. However, children with ASD have previously presented with reduced range of motion at the ankle and increased ankle joint stiffness during gait. Therefore, if the ankle function is compromised in children with ASD, they may have difficulty when changing speed or different joints will have to compensate.

The third chapter evaluated MOS_{ML} and MOS_{AP} to quantify dynamic stability in this population. Upon examination of MOS_{ML} and MOS_{AP}, children with ASD did not demonstrate any changes in dynamic stability among the three speed conditions. While they were able to alter their stride characteristics, their MOS in the fast and slow speed were not significantly different from their preferred MOS. The large variation in MOS_{ML} and MOS_{AP} may indicate the need for single subject studies to evaluate if some children with ASD are particularly unstable at certain speeds. However, the findings from this study suggest that dynamic stability may be relatively unaffected in different gait speeds, and that postural instability and increased postural sway in this population may be limited to static posture.

The fourth chapter confirmed that children with ASD present with reduced cognitive abilities and processing in the areas of executive function, attention, and processing speed, when compared to children with NT. However, children with ASD did not demonstrate differences in walking velocity, WSR, or kinematic strategies compared to the NT group. Additionally, there were no significant correlations between cognitive assessments and gait variables in the ASD. The NT group displayed several correlations between scores on executive function and attention assessments and gait variables. This may suggest that walking may not be a purely automatic task, and when deviating from a learned pattern, cognitive resources may come into play. Based on the findings of the current study, children with ASD do not utilize executive function, attention, or processing speed to change their gait speed, which could be due to their limited cognitive resources and slower cognitive processes. However, more demanding motor tasks,

such as dual task conditions or walking on different surfaces, may make the relationship between cognitive abilities and gait parameters more visible.

In conclusion, the information gleaned from this multi-aim project has provided insight into the mobility mechanisms involved in changing gait speed in children with ASD, as well as their cognitive abilities and how that impacts their capability to change their walking speed. Particularly, it has revealed the primary kinematic strategy to change gait speed may involve the ankle joint in children with ASD. Additionally, dynamic stability is not altered in fast or slow walking conditions. Lastly, reduced cognitive abilities and slower cognitive processing in areas of executive function, attention, and processing speed do not play a role in how children with ASD are able to change their walking speed. Children with ASD also appear to mechanically alter their speed in a similar fashion to NT children. This research adds to the growing body of literature on motor deficits and overall locomotion in the ASD population. The findings also prompt further research questions that can be evaluated and contribute to the research in this area. More research in this area will aid in future diagnosis methods or interventions for children with ASD.

REFERENCES

Ambrosini, D., Courchesne, E., & Kaufman, K. R. (1998). Motion analysis of patients with infantile autism. *Gait and Posture, 7*(2), 188.

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders (DSM-5®)* American Psychiatric Pub.

Belmonte, M. K., & Yurgelun-Todd, D. A. (2003). Functional anatomy of impaired selective attention and compensatory processing in autism. *Cognitive Brain Research, 17*(3), 651-664.

Ble, A., Volpato, S., Zuliani, G., Guralnik, J. M., Bandinelli, S., Lauretani, F., . . . Ferrucci, L. (2005). Executive function correlates with walking speed in older persons: The InCHIANTI study. *Journal of the American Geriatrics Society, 53*(3), 410-415.

Boucher, J. (2008). *The autistic spectrum: Characteristics, causes and practical issues* Sage.

Bruijn, S. M., Meijer, O., Beek, P., & van Dieen, J. H. (2013). Assessing the stability of human locomotion: A review of current measures. *Journal of the Royal Society Interface, 10*(83), 20120999.

Brunsdon, V. E., Colvert, E., Ames, C., Garnett, T., Gillan, N., Hallett, V., . . . Happé, F. (2015). Exploring the cognitive features in children with autism spectrum disorder, their co-twins, and typically developing children within a population-based sample. *Journal of Child Psychology and Psychiatry, 56*(8), 893-902.

Caderby, T., Yiou, E., Peyrot, N., Begon, M., & Dalleau, G. (2014). Influence of gait speed on the control of mediolateral dynamic stability during gait initiation. *Journal of Biomechanics, 47*(2), 417-423.

Callisaya, M. L., Launay, C. P., Srikanth, V. K., Verghese, J., Allali, G., & Beauchet, O. (2017). Cognitive status, fast walking speed and walking speed reserve—the gait and alzheimer interactions tracking (GAIT) study. *Geroscience, 39*(2), 231-239.

Callisaya, M., Blizzard, L., McGinley, J. L., & Srikanth, V. (2012). Risk of falls in older people during fast-walking–the TASCOG study. *Gait & Posture, 36*(3), 510-515.

Chen, I., Kuo, K., & Andriacchi, T. (1997). The influence of walking speed on mechanical joint power during gait. *Gait & Posture, 6*(3), 171-176.

Cole, M. H., Sweeney, M., Conway, Z. J., Blackmore, T., & Silburn, P. A. (2017). Imposed faster and slower walking speeds influence gait stability differently in parkinson fallers. *Archives of Physical Medicine and Rehabilitation, 98*(4), 639-648.

Cook, J. (2016). From movement kinematics to social cognition: The case of autism. *Philosophical Transactions of the Royal Society B: Biological Sciences, 371*(1693), 20150372.

Deshpande, N., Metter, E. J., Bandinelli, S., Guralnik, J., & Ferrucci, L. (2009). Gait speed under varied challenges and cognitive decline in older persons: A prospective study. *Age and Ageing, 38*(5), 509-514.

Dichter, G. S., Radonovich, K. J., Turner-Brown, L. M., Lam, K. S., Holtzclaw, T. N., & Bodfish, J. W. (2010). Performance of children with autism spectrum disorders on the dimension-change card sort task. *Journal of Autism and Developmental Disorders, 40*(4), 448-456.

Dingwell, J. B., & Cusumano, J. P. (2000). Nonlinear time series analysis of normal and pathological human walking. *Chaos: An Interdisciplinary Journal of Nonlinear Science, 10*(4), 848-863.

Donohue, S. E., Darling, E. F., & Mitroff, S. R. (2012). Links between multisensory processing and autism. *Experimental Brain Research, 222*(4), 377-387.

Dufek, J., Eggleston, J., Harry, J., & Hickman, R. (2017). A comparative evaluation of gait between children with autism and typically developing matched controls. *Medical Sciences, 5*(1), 1.

Dyck, M. J., Hay, D., Anderson, M., Smith, L. M., Piek, J., & Hallmayer, J. (2004). Is the discrepancy criterion for defining developmental disorders valid? *Journal of Child Psychology and Psychiatry, 45*(5), 979-995.

Eggleston, J. D., Harry, J. R., Cereceres, P. A., Olivas, A. N., Chavez, E. A., Boyle, J. B., & Dufek, J. S. (2020). Lesser magnitudes of lower extremity variability during terminal swing characterizes walking patterns in children with autism. *Clinical Biomechanics, ,* 105031.

Eggleston, J. D., Harry, J. R., & Dufek, J. S. (2018). Lower extremity joint stiffness during walking distinguishes children with and without autism. *Human Movement Science, 62*, 25-33.

Eggleston, J. D., Harry, J. R., Hickman, R. A., & Dufek, J. S. (2017). Analysis of gait symmetry during over-ground walking in children with autism spectrum disorder. *Gait & Posture, 55*, 162-166.

Eggleston, J. D., Landers, M. R., Bates, B. T., Nagelhout, E., & Dufek, J. S. (2018). Examination of gait parameters during perturbed over-ground walking in children with autism spectrum disorder. *Research in Developmental Disabilities, 74*, 50-56.

England, S. A., & Granata, K. P. (2007). The influence of gait speed on local dynamic stability of walking. *Gait & Posture, 25*(2), 172-178.

Falter, C. M., Noreika, V., Wearden, J. H., & Bailey, A. J. (2012). More consistent, yet less sensitive: Interval timing in autism spectrum disorders. *Quarterly Journal of Experimental Psychology, 65*(11), 2093-2107.

Fan, Y., Li, Z., Han, S., Lv, C., & Zhang, B. (2016). The influence of gait speed on the stability of walking among the elderly. *Gait & Posture, 47*, 31-36.

Fitzpatrick, A. L., Buchanan, C. K., Nahin, R. L., DeKosky, S. T., Atkinson, H. H., Carlson, M. C., & Williamson, J. D. (2007). Associations of gait speed and other measures of physical function with cognition in a healthy cohort of elderly persons. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 62*(11), 1244-1251.

Floris, D. L., Barber, A. D., Nebel, M. B., Martinelli, M., Lai, M., Crocetti, D., . . . Mostofsky, S. H. (2016). Atypical lateralization of motor circuit functional connectivity in children with autism is associated with motor deficits. *Molecular Autism, 7*(1), 35.

Fournier, K. A., Hass, C. J., Naik, S. K., Lodha, N., & Cauraugh, J. H. (2010). Motor coordination in autism spectrum disorders: A synthesis and meta-analysis. *Journal of Autism and Developmental Disorders, 40*(10), 1227-1240.

Fournier, K. A., Kimberg, C. I., Radonovich, K. J., Tillman, M. D., Chow, J. W., Lewis, M. H., . . . Hass, C. J. (2010). Decreased static and dynamic postural control in children with autism spectrum disorders. *Gait & Posture, 32*(1), 6-9.

Fukuchi, C. A., Fukuchi, R. K., & Duarte, M. (2019). Effects of walking speed on gait biomechanics in healthy participants: A systematic review and meta-analysis. *Systematic Reviews, 8*(1), 1-11.

Green, D., Charman, T., Pickles, A., Chandler, S., Loucas, T., Simonoff, E., & Baird, G. (2009). Impairment in movement skills of children with autistic spectrum disorders. *Developmental Medicine & Child Neurology, 51*(4), 311-316.

Hanlon, M., & Anderson, R. (2006). Prediction methods to account for the effect of gait speed on lower limb angular kinematics. *Gait & Posture, 24*(3), 280-287.

Hausdorff, J. M., Yogev, G., Springer, S., Simon, E. S., & Giladi, N. (2005). Walking is more like catching than tapping: Gait in the elderly as a complex cognitive task. *Experimental Brain Research, 164*(4), 541-548.

Hebenstreit, F., Leibold, A., Krinner, S., Welsch, G., Lochmann, M., & Eskofier, B. M. (2015). Effect of walking speed on gait sub phase durations. *Human Movement Science, 43*, 118-124.

Helbostad, J. L., & Moe-Nilssen, R. (2003). The effect of gait speed on lateral balance control during walking in healthy elderly. *Gait & Posture, 18*(2), 27-36.

Hof, A., Gazendam, M., & Sinke, W. (2005). The condition for dynamic stability. *Journal of Biomechanics, 38*(1), 1-8.

Hof, A. L., van Bockel, R. M., Schoppen, T., & Postema, K. (2007). Control of lateral balance in walking: Experimental findings in normal subjects and above-knee amputees. *Gait & Posture, 25*(2), 250-258.

Hollman, J. H., Watkins, M. K., Imhoff, A. C., Braun, C. E., Akervik, K. A., & Ness, D. K. (2016). A comparison of variability in spatiotemporal gait parameters between treadmill and overground walking conditions. *Gait & Posture, 43*, 204-209.

Holtzer, R., Verghese, J., Xue, X., & Lipton, R. B. (2006). Cognitive processes related to gait velocity: Results from the einstein aging study. *Neuropsychology, 20*(2), 215.

Johnson, K. A., Robertson, I. H., Kelly, S. P., Silk, T. J., Barry, E., Dáibhis, A., . . . Gallagher, L. (2007). Dissociation in performance of children with ADHD and high-functioning autism on a task of sustained attention. *Neuropsychologia, 45*(10), 2234-2245.

Joseph, R. M., McGrath, L. M., & Tager-Flusberg, H. (2005). Executive dysfunction and its relation to language ability in verbal school-age children with autism. *Developmental Neuropsychology, 27*(3), 361-378.

Kas, M. J., Glennon, J. C., Buitelaar, J., Ey, E., Biemans, B., Crawley, J., . . . Talpos, J. (2014). Assessing behavioural and cognitive domains of autism spectrum disorders in rodents: Current status and future perspectives. *Psychopharmacology, 231*(6), 1125-1146.

Kharb, A., Saini, V., Jain, Y., & Dhiman, S. (2011). A review of gait cycle and its parameters. *IJCEM International Journal of Computational Engineering & Management, 13*, 78-83.

Kohen-Raz, R., Volkman, F. R., & Cohen, D. J. (1992). Postural control in children with autism. *Journal of Autism and Developmental Disorders, 22*(3), 419-432.

Krebs, D. E., Goldvasser, D., Lockert, J. D., Portney, L. G., & Gill-Body, K. M. (2002). Is base of support greater in unsteady gait? *Physical Therapy, 82*(2), 138-147.

Lai, M., Lombardo, M. V., Ruigrok, A. N., Chakrabarti, B., Wheelwright, S. J., Auyeung, B., . . . MRC AIMS Consortium. (2012). Cognition in males and females with autism: Similarities and differences. *PLoS One, 7*(10), e47198.

Lee, A., Bhatt, T., Smith-Ray, R. L., Wang, E., & Pai, Y. (2019). Gait speed and dynamic stability decline accelerates only in late life: A cross-sectional study in community-dwelling older adults. *Journal of Geriatric Physical Therapy (2001), 42*(2), 73.

Leigh, J. P., & Du, J. (2015). Brief report: Forecasting the economic burden of autism in 2015 and 2025 in the united states. *Journal of Autism and Developmental Disorders, 45*(12), 4135-4139.

Lelas, J. L., Merriman, G. J., Riley, P. O., & Kerrigan, D. C. (2003). Predicting peak kinematic and kinetic parameters from gait speed. *Gait & Posture, 17*(2), 106-112.

Lezak, M. D., Howieson, D. B., Loring, D. W., & Fischer, J. S. (2004). *Neuropsychological assessment* Oxford University Press, USA.

Lim, Y. H., Partridge, K., Girdler, S., & Morris, S. L. (2017). Standing postural control in individuals with autism spectrum disorder: Systematic review and meta-analysis. *Journal of Autism and Developmental Disorders, 47*(7), 2238-2253.

Lord, C., Elsabbagh, M., Baird, G., & Veenstra-Vanderweele, J. (2018). Autism spectrum disorder. *The Lancet, 392*(10146), 508-520.

Lum, J. A., Shandley, K., Albein-Urios, N., Kirkovski, M., Papadopoulos, N., Wilson, R. B., . . . Rinehart, N. J. (2020). Meta-Analysis reveals gait anomalies in autism. *Autism Research,*

Maenner, M. J., Shaw, K. A., & Baio, J. (2020). Prevalence of autism spectrum disorder among children aged 8 years—autism and developmental disabilities monitoring network, 11 sites, united states, 2016. *MMWR Surveillance Summaries, 69*(4), 1.

Maki, B. E. (1997). Gait changes in older adults: Predictors of falls or indicators of fear? *Journal of the American Geriatrics Society, 45*(3), 313-320.

Manicolo, O., Brotzmann, M., Hagmann-von Arx, P., Grob, A., & Weber, P. (2019). Gait in children with infantile/atypical autism: Age-dependent decrease in gait variability and associations with motor skills. *European Journal of Paediatric Neurology, 23*(1), 117-125.

Matson, M. L., Matson, J. L., & Beighley, J. S. (2011). Comorbidity of physical and motor problems in children with autism. *Research in Developmental Disabilities, 32*(6), 2304-2308.

McPhillips, M., Finlay, J., Bejerot, S., & Hanley, M. (2014). Motor deficits in children with autism spectrum disorder: A cross-syndrome study. *Autism Research, 7*(6), 664-676.

Middleton, A., Fulk, G. D., Herter, T. M., Beets, M. W., Donley, J., & Fritz, S. L. (2016). Self-selected and maximal walking speeds provide greater insight into fall status than walking speed reserve among community-dwelling older adults. *American Journal of Physical Medicine & Rehabilitation, 95*(7), 475-482. doi:10.1097/PHM.0000000000000488 [doi]

Minshew, N. J., Sung, K., Jones, B. L., & Furman, J. M. (2004). Underdevelopment of the postural control system in autism. *Neurology, 63*(11), 2056-2061. doi:63/11/2056 [pii]

Molloy, C. A., Dietrich, K. N., & Bhattacharya, A. (2003). Postural stability in children with autism spectrum disorder. *Journal of Autism and Developmental Disorders, 33*(6), 643-652.

Morris, M. E., Iansek, R., Matyas, T. A., & Summers, J. J. (1994). The pathogenesis of gait hypokinesia in parkinson's disease. *Brain, 117*(5), 1169-1181.

Morrison, S., Armitano, C. N., Raffaele, C. T., Deutsch, S. I., Neumann, S. A., Caracci, H., & Urbano, M. R. (2018). Neuromotor and cognitive responses of adults with autism spectrum disorder compared to neurotypical adults. *Experimental Brain Research, 236*(8), 2321-2332.

Narzisi, A., Muratori, F., Calderoni, S., Fabbro, F., & Urgesi, C. (2013). Neuropsychological profile in high functioning autism spectrum disorders. *Journal of Autism and Developmental Disorders, 43*(8), 1895-1909.

Nayate, A., Tonge, B. J., Bradshaw, J. L., McGinley, J. L., Iansek, R., & Rinehart, N. J. (2012). Differentiation of high-functioning autism and asperger's disorder based on neuromotor behaviour. *Journal of Autism and Developmental Disorders, 42*(5), 707-717.

Nobile, M., Perego, P., Piccinini, L., Mani, E., Rossi, A., Bellina, M., & Molteni, M. (2011). Further evidence of complex motor dysfunction in drug naive children with autism using automatic motion analysis of gait. *Autism, 15*(3), 263-283.

Nutt, J., Marsden, C., & Thompson, P. (1993). Human walking and higher level gait disorders, particularly in the elderly. *Neurology-Minneapolis-, 43*, 268-268.

Pan, C., Tsai, C., & Chu, C. (2009). Fundamental movement skills in children diagnosed with autism spectrum disorders and attention deficit hyperactivity disorder. *Journal of Autism and Developmental Disorders, 39*(12), 1694.

Papadopoulos, N., McGinley, J. L., Bradshaw, J. L., & Rinehart, N. J. (2014). An investigation of gait in children with attention deficit hyperactivity disorder: A case controlled study. *Psychiatry Research, 218*(3), 319-323.

Peebles, A. T., Reinholdt, A., Bruetsch, A. P., Lynch, S. G., & Huisinga, J. M. (2016). Dynamic margin of stability during gait is altered in persons with multiple sclerosis. *Journal of Biomechanics, 49*(16), 3949-3955.

Persad, C. C., Jones, J. L., Ashton-Miller, J. A., Alexander, N. B., & Giordani, B. (2008). Executive function and gait in older adults with cognitive impairment. *The Journals of Gerontology Series A: Biological Sciences and Medical Sciences, 63*(12), 1350-1355.

Rajendran, G., & Mitchell, P. (2007). Cognitive theories of autism. *Developmental Review, 27*(2), 224-260.

Rancho Los Amigos National Rehabilitation Center. (2001). Observational gait analysis.*4th ed*(Los Amigos Research and Education Institute, Rancho Los Amigos National Rehabilitation Center: Downey, CA, USA)

Remelius, J. G., Jones, S. L., House, J. D., Busa, M. A., Averill, J. L., Sugumaran, K., . . . Van Emmerik, R. E. (2012). Gait impairments in persons with multiple sclerosis across preferred and fixed walking speeds. *Archives of Physical Medicine and Rehabilitation, 93*(9), 1637-1642.

Riley, P. O., Della Croce, U., & Kerrigan, D. C. (2001). Propulsive adaptation to changing gait speed. *Journal of Biomechanics, 34*(2), 197-202.

Rinehart, N. J., Tonge, B. J., Bradshaw, J. L., Iansek, R., Enticott, P. G., & Johnson, K. A. (2006). Movement-related potentials in high-functioning autism and asperger's disorder. *Developmental Medicine & Child Neurology, 48*(4), 272-277.

Rinehart, N. J., Tonge, B. J., Iansek, R., McGinley, J., Brereton, A. V., Enticott, P. G., & Bradshaw, J. L. (2006). Gait function in newly diagnosed children with autism: Cerebellar and basal ganglia related motor disorder. *Developmental Medicine and Child Neurology, 48*(10), 819-824.

Robinson, S., Goddard, L., Dritschel, B., Wisley, M., & Howlin, P. (2009). Executive functions in children with autism spectrum disorders. *Brain and Cognition, 71*(3), 362-368.

Sheridan, P. L., & Hausdorff, J. M. (2007). The role of higher-level cognitive function in gait: Executive dysfunction contributes to fall risk in alzheimer's disease. *Dementia and Geriatric Cognitive Disorders, 24*(2), 125-137.

Shetreat-Klein, M., Shinnar, S., & Rapin, I. (2014). Abnormalities of joint mobility and gait in children with autism spectrum disorders. *Brain and Development, 36*(2), 91-96.

Sinzig, J., Bruning, N., Morsch, D., & Lehmkuhl, G. (2008). Attention profiles in autistic children with and without comorbid hyperactivity and attention problems. *Acta Neuropsychiatrica, 20*(4), 207-215.

Sivakumaran, S., Schinkel-Ivy, A., Masani, K., & Mansfield, A. (2018). Relationship between margin of stability and deviations in spatiotemporal gait features in healthy young adults. *Human Movement Science, 57*, 366-373.

Stansfield, B., Hillman, S., Hazlewood, M., & Robb, J. (2006). Regression analysis of gait parameters with speed in normal children walking at self-selected speeds. *Gait & Posture, 23*(3), 288-294.

van der Linden, Mariëtta L, Kerr, A. M., Hazlewood, M. E., Hillman, S. J., & Robb, J. E. (2002). Kinematic and kinetic gait characteristics of normal children walking at a range of clinically relevant speeds. *Journal of Pediatric Orthopaedics, 22*(6), 800-806.

Vernazza-Martin, S., Martin, N., Vernazza, A., Lepellec-Muller, A., Rufo, M., Massion, J., & Assaiante, C. (2005). Goal directed locomotion and balance control in autistic children. *Journal of Autism and Developmental Disorders, 35*(1), 91-102.

Vilensky, J. A., Damasio, A. R., & Maurer, R. G. (1981). Gait disturbances in patients with autistic behavior: A preliminary study. *Archives of Neurology, 38*(10), 646-649.

Webster, K. E., Merory, J. R., & Wittwer, J. E. (2006). Gait variability in community dwelling adults with alzheimer disease. *Alzheimer Disease & Associated Disorders, 20*(1), 37-40.

Weiss, M. J., Moran, M. F., Parker, M. E., & Foley, J. T. (2013). Gait analysis of teenagers and young adults diagnosed with autism and severe verbal communication disorders. *Frontiers in Integrative Neuroscience, 7*, 33.

Winter, D. A. (1983). Biomechanical motor patterns in normal walking. *Journal of Motor Behavior, 15*(4), 302-330.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi, N. (2008). The role of executive function and attention in gait. *Movement Disorders: Official Journal of the Movement Disorder Society, 23*(3), 329-342.

Young, P. M. M., & Dingwell, J. B. (2012). Voluntary changes in step width and step length during human walking affect dynamic margins of stability. *Gait & Posture, 36*(2), 219-224.

Yu, H., Riskowski, J., Brower, R., & Sarkodie-Gyan, T. (2009). Gait variability while walking with three different speeds. Paper presented at the *2009 IEEE International Conference on Rehabilitation Robotics*, 823-827.

Zeni Jr, J., Richards, J., & Higginson, J. (2008). Two simple methods for determining gait events during treadmill and overground walking using kinematic data. *Gait & Posture, 27*(4), 710-714.

CURRICULUM VITA

Alyssa Olivas received her Bachelor of Science with Honors in Biology from the University of Texas at El Paso (UTEP) in 2017. Alyssa was awarded several scholarships to fund her PhD at UTEP, including the UTEP Doctoral Excellence Scholarship, the UTEP Graduate Scholarship, and the Eloise E. and Patrick B. Wieland Graduate Fellows Endowment. She conducted her research with the Gait Research and Movement Analysis Laboratory at UTEP and focused on pediatric gait analysis and Autism Spectrum Disorder motor and gait deficits. Alyssa has co-authored two peer-reviewed publications and presented podium and poster presentations at several national and international academic conferences. While pursuing her studies and research, Alyssa served as the head teaching assistant for an undergraduate biomechanics laboratory, and was responsible for creating content, giving lectures, and assisting students with assignments.

Contact Information: anolivas4@miners.utep.edu