FRAC TAL DYNAMICS OF CIRCLE DRAWING IN CHILDREN WITH ASD

by

Amanda Fleury

A thesis submitted in conformity with the requirements for the degree of Master of Applied Science
Graduate Department of Biomaterials & Biomedical Engineering
University of Toronto

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Abstract

Fractal dynamics of circle drawing in children with ASD

Amanda Fleury

Master of Applied Science

Graduate Department of Biomaterials & Biomedical Engineering

University of Toronto

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Sensory motor deficits, although not part of the diagnostic criteria, are frequently reported in autism spectrum disorder (ASD). The objective of this project is to study the temporal and spatial dynamics of an approximately periodic motor activity (circle drawing) in children with ASD. The natural rhythm of periodic motor activities such as circle drawing are known to exhibit statistical persistence in typically developing individuals.

A sample of 15 children aged 4 to 8 years, with a primary diagnosis of ASD were asked to draw circles using a computerized tablet and pen, which record spatio-temporal data. Results were compared with those of 19 typically developing children. While no differences were seen in statistical persistence, differences were observed in timing of discontinuous circle drawing and in kinetic process variable such as grip and axial forces. Understanding the specific nature of graphomotor deficits is the first step towards developing targeted treatment for these impairments.
Dedication

To my parents, who have always supported me, and my brother, who understands.
Acknowledgements

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>ADI-R</td>
<td>Autism Diagnostic Interview - Revised</td>
</tr>
<tr>
<td>ADOS</td>
<td>Autism Diagnostic Observation Schedule</td>
</tr>
<tr>
<td>ASD</td>
<td>Autism Spectrum Disorder</td>
</tr>
<tr>
<td>BOTMP</td>
<td>Bruininks-Oseretsky Test of Motor Prociency</td>
</tr>
<tr>
<td>CV</td>
<td>Coefficient of Variation</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>DD</td>
<td>Developmental Disability</td>
</tr>
<tr>
<td>DFA</td>
<td>Detrended Fluctuation Analysis</td>
</tr>
<tr>
<td>DSM-IV</td>
<td>Diagnostic and Statistical Manual of Mental Disorders - Fourth Edition</td>
</tr>
<tr>
<td>fBm</td>
<td>Fractal Brownian Motion</td>
</tr>
<tr>
<td>fGn</td>
<td>Fractal Gaussian Noise</td>
</tr>
<tr>
<td>FSIQ</td>
<td>Full Scale Intelligence Quotient</td>
</tr>
<tr>
<td>IQ</td>
<td>Intelligence Quotient</td>
</tr>
<tr>
<td>LD</td>
<td>Learning Disability</td>
</tr>
<tr>
<td>M-ABC</td>
<td>Movement Assessment Battery for Children</td>
</tr>
<tr>
<td>NVIQ</td>
<td>Non Verbal Intelligence Quotient</td>
</tr>
<tr>
<td>PDMS</td>
<td>Peabody Developmental Motor Scales</td>
</tr>
<tr>
<td>PSD</td>
<td>Power Spectral Density</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Squared</td>
</tr>
<tr>
<td>SSC</td>
<td>Signal Summation Conversion</td>
</tr>
<tr>
<td>TD</td>
<td>Typically Developing</td>
</tr>
</tbody>
</table>
Chapter 1

Introduction

1.1 Motivation

Autism spectrum disorder (ASD) is a group of neurodevelopmental disorders, clinically characterized by impairment in three core areas: a) communication skills; b) social interactions; and c) restricted, repetitive and stereotyped behaviors, interests or activities (DSM-IV). In addition to these core deficits, ASDs are also associated with impairments in other domains. For example, ASD is associated with atypical patterns in visual perception [1], visual-motor integration [2, 3], and fine motor skills [4]. Motor difficulties, in particular, are highly prevalent in individuals with ASD, although these difficulties do not constitute a diagnostic criterion.

Many standardized tests exist to characterize motor differences in children, such as the Bruininks-Oseretsky Test of Motor Proficiency (BOTMP), Movement Assessment Battery for Children (Movement ABC), and the Peabody Developmental Motor Scales (PDMS). For tests such as these, clinicians observe a variety of gross and fine motor tasks to qualitatively and quantitatively assess motor performance. These standardized clinical tests evaluate motor output and performance, but they do not provide any information about the underlying dynamics that produce movement [5]. We are, however, interested
in graphomotor abilities (e.g. handwriting and drawing) in this population, which are inherently dynamic processes that involve an intricate interplay of biomechanical mechanisms over time. To study this dynamic nature of motor performance, computer-based techniques using a force sensitive tablet have been employed [6, 7]. Most recently force-sensitive writing utensils have been proposed as a complement to standardized clinical tests for analyzing graphomotor skills [8–11]. Computer-based techniques provide measurement and analysis of dynamic characteristics, such as velocity, consistency, and pressure of fine motor control.

The dynamic nature of graphomotor abilities has not been investigated in ASD. However, there is emerging evidence suggesting that ASD may be associated with atypical biomechanical control in graphomotor tasks. In particular, ASD is associated with varying degrees of impairment in organization, planning and execution of movement [12, 13], which affect control of writing or drawing instruments. Timing and coordination of movement has also been shown to be impaired in this population [14–16], and statistical persistence has previously been shown to distinguish between populations with similar deficits in coordination and timing of movements [17, 18]. In order to better understand timing deficits in children with ASD, the current study investigates statistical persistence and timing parameters in a graphomotor task.

Compromised kinetic control, due for example to hypotonia [19] and weak grip strength [20] can affect the effort required to hold a pen and therefore the quality of writing over time [21]. Coordination of grip and load forces, essential for control and quality of writing [21], is reportedly impaired in children with ASD [22]. To further the understanding of the biomechanical underpinnings of graphomotor difficulties in ASD, the present study investigated the kinetic characteristics of a graphomotor task using a digitizing tablet and force-sensitive pen. Differences in dynamics observed in young children may aid in early intervention and targeted treatment of motor impairments [5].
1.2 Research questions and objectives

1.2.1 Primary Research Question and Objectives

We describe an experiment to study the statistical persistence and pacing of a cyclic, ballistic drawing task in children diagnosed with ASD. This estimate, along with additional measures of timing consistency, will allow us to describe deficits associated with timing in children with ASD.

The experimental paradigms have been designed to allow us to leverage the body of literature on human gait and handwriting analysis on the healthy pediatric sample and draw parallels from quantitative models in that field. In the interest of studying the dynamics of movement and movement timing in children with ASD, the following research question was proposed:

*In what ways, if any, are the temporal dynamics of a cyclic, ballistic drawing task different between children with ASD and children who are typically developing?*

In order to address this research question, we identified several primary objectives. We planned to *a*) investigate the temporal fractal dynamics for a circle drawing task in children with ASD; *b*) investigate how age relates to fractal dynamics as compared to typically developing controls; and *c*) investigate the timing of event-based and emergent tasks in children with ASD.

1.2.2 Secondary Research Question and Objectives

Graphomotor proficiency has aspects of both rate and quality [23], and while the first research question addresses issues of rate and timing, I also wanted to investigate aspects of quality in circle drawing, and their relationship to kinetic process variables. In this light, the following secondary research question was proposed:
Chapter 1. Introduction

How do the quality of circle drawing and kinetic variables differ between children with ASD and children who are typically developing?

In order to address this secondary research question, we identified several secondary objectives. We desired to a) investigate various measures of quality including circle size, roundness, and consistency; b) investigate kinetic variables, such as grip and axial forces, as compared to typically developing controls.

1.3 Overview

The following chapter, Chapter 2, gives background information relevant to the understanding of the thesis. Beginning with a brief explanation of ASD and associated symptoms, particularly as related to movement difficulties, the chapter then describes previous research related to graphomotor activities, specifically circle drawing. Circle drawing has aspects of timing as well as quality, which are briefly described.

The following chapters describe a study investigating circle drawing in children with ASD. Chapter 3 addresses the first research objective, outlining analysis of statistical persistence and continuous vs. discontinuous timing characteristics in children with ASD. Chapter 4 looks at the second research objective, providing an examination of spatial and kinetic characteristics, as well as the relationship between various process variables of circle drawing in children with ASD. Finally, Chapter 5 summarizes the main conclusions and contributions resulting from this work.

The body of this thesis (Chapters 3 and 4) consists of a compilation of two journal articles (both under review at the time of defense) arising from a single study. Study protocol (including equipment, data collection and analysis) is described in greatest detail in Chapter 3 (section 3.3), such that section 4.3 contains primarily repeated content. In addition, chapter introductions (sections 3.2 and 4.2) contain some repeated background information from Chapter 2.
Chapter 2

Background

2.1 Autism and Motor Difficulties

Autism spectrum disorder (ASD) is a group of neurodevelopmental disorders, clinically characterized by impairments in social communication skills and restricted/repetitive behaviors (DSM-IV). The pervasive nature of the disorder makes it difficult to pinpoint a single cause or mechanism, and instead diagnosis is based on a battery of qualitative behavioral tests. Various studies have been done to identify potential biomarkers for ASD, including motor development tests [24], metabolic studies [25], environmental susceptibility [26] and tests for specific genetic markers [27]. These studies provide promising research into early physiological biomarkers for ASD, but behavioral tests still dominate the diagnostic landscape.

Studies of gait and reaching/grasping have provided evidence of motor difficulties in ASD, but the available data are inconsistent. A small study by Hughes [14] showed qualitative impairment in the “reach, grasp, and place” task, indicating motor planning deficits for goal directed sequences. In a kinematic study, the “reach and grasp” movement in children with autism was compared to the same movement in healthy controls. Abnormalities were noted in the speed of different phases of the movement in a way that
is similar to Parkinson’s disease, possibly implicating the basal ganglia in the pathophysiology of such deficits in autism [15]. This finding was consistent with an earlier kinesiologic study of gait in children with autism that reported abnormalities in stride length, stance time, hip flexion and knee extension, resembling the gait of adults with Parkinson’s [16]. Deficits in anticipatory function seen in anticipatory postural adjustments were identified in children with autism by Schmitz et al. [28]. Together, these studies suggest that differences in movement patterns in ASD appear to be related to the speed and timing of different phases of movement.

In addition to impairments in gross motor function, various studies have shown difficulties in fine motor tasks in children with ASD. Graphomotor skills, which are important for success in school, communication, and building children’s self-esteem [29], have been observed to be poor in individuals with autism. In his original description of autism, Asperger noted motor incoordination and handwriting impairments in a number of the subjects [30]. More recently, various studies have investigated handwriting and fine motor impairments in children with ASD. For example, in a comparison of individuals with ASD against those with learning disabilities (LD), Miyahara et al. [31] found that both groups performed poorly in tests of manual dexterity. Macrographia (abnormally large handwriting) has been observed among subjects with ASD when their handwriting was compared against that of age- and IQ-matched controls [32]. Children with ASD also performed poorly on the Minnesota Handwriting Assessment compared to controls [33]. More specifically, the study found that children with ASD showed worse quality of forming letters but did not show differences in their ability to correctly size, align, and space their letters, contrary to earlier studies observing macrographia in children with ASD. The Sequential Handwriting Process was proposed by Cartmill et al. [34] as a suitable vehicle to study handwriting in ASD. They found that the handwriting of children with ASD was slower and less legible than that of the comparison children, but the differences were not significant. However, accuracy of letter formation was found to be significantly
worse for children with ASD. Although most of these studies provide evidence that there is some abnormality in the motor system in autism, the data are far from consistent at this point.

As a potential explanation for these motor difficulties, many studies point to differences in the cerebellum [35] and the basal ganglia [15] in children with ASD, since both are involved to some degree in movement coordination and planning. Several studies have identified structural differences in the cerebellum of children with ASD compared to typically developing controls, but here as well the data are inconclusive. Older studies looked at the cross-sectional area of different parts of the brain and cerebellum, with some papers reporting reduced cerebellar area in specific regions [36–41], and others reporting no differences [42–45]. More recent studies have analyzed the volume of different brain structures, including the cerebellum, again with some finding reduced volume in specific areas [46–48], and others reporting no difference [49].

2.2 Circle Drawing

Circles have been shown to emerge very early on in the drawings of young children. Children can distinguish perceptually between circles and other shapes by their first birthday and can reproduce circular shapes at approximately 3 years old [50]. This is one of the first shapes to be acquired and is therefore mastered at a young age compared to more difficult shapes such as triangles and squares [51]. Because of the relative task simplicity and the abundance of parameters that can be controlled and assessed, there is a large body of literature relating to circle drawing. Studies have investigated many aspects of circle drawing behavior in young children as well as adults, including circling direction, speed, timing, developmental patterns, and effects of handedness, age, and gender. Studies, however, often report conflicting results. For example, Rueckriegel et al. [51] found that male subjects drew at significantly higher speeds than female subjects.
in a circle drawing task and concluded that future analyses of impaired movement in children and adolescents need to take age and gender into consideration. In contrast, van Mier [52] found no significant gender differences in terms of speed or accuracy in a timed drawing task.

Results do however show that there is an observable developmental trajectory in any drawing task. Researchers have concluded that the age of completed maturation depends on the task complexity. As well, speed, automation and pressure increase with age, whereas variability decreases [51]. Specifically looking at circles, Robertson [53] found that younger children (age 4–7) produced larger circles with longer durations than those of older children (age 8–10) and adults. Lange-Küttner [54] studied drawing in 4–6 year olds and found that older children applied higher pressure, possibly indicating a generally greater tension when drawing. In a bimanual task, Ringenbach and Amazeen [55] showed that 4–6 year old children produced much larger amplitudes than required and noted that the amplitude of their movements increased with drawing rate more so than in older children and adults.

Lantero and Ringenbach [56] demonstrated that due to attentional demands, the length of time spent performing a drawing task needs to be constrained in the study design, as fatigue and boredom may increase as the trial goes on, causing changing dynamics. This is especially relevant in a population known to have problems with concentration and attention.

## 2.3 Timing

Control and production of timed and coordinated movements are important aspects of skilled motor behaviour [57]. As such, timing processes in motor control have been extensively studied [58–61]. Robertson et al. [58] and later Zelaznik et al. [57] found no significant correlation between finger tapping and continuous circle drawing tasks, indicat-
ing that at least two different timing processes are used in motor control. The authors characterized circle drawing as a continuous (or emergent) task, and tapping as a discontinuous (or event-based) task. The works of Ivry et al. [62] and Spencer et al. [59] showed that the timing variability in a continuous circle drawing task is not affected in patients with cerebellum dysfunction, however timing of a discontinuous task is affected, indicating that event-based timing relies to some level on the cerebellum.

In several studies further supporting this view, Bo et al. found high temporal variability in discontinuous but not continuous drawing tasks in young children [63]. The authors later conducted a similar study in children with developmental coordination disorder and found a small subgroup with reduced ability on the discontinuous task, indicating possible cerebellar impairments [64]. Biberstine et al. [65] found no effect of spatial precision on temporal variability in circle drawing, and no effect of method of circle scoring, addressing some of the earlier criticisms of the work by Ivry et al. [62], and providing support for the event and emergent timing frameworks.

### 2.4 Fractals

Temporal precision and variability has been previously measured using the coefficient of variation. This approach assumes that timing variations are uncorrelated between cycles. Contradicting this assumption, long-term correlations or statistical persistence (fractal patterns) have been reported in time series of repetitive circle drawing cycle times [66], finger-tapping intervals [67], and stride intervals in human gait [18, 61, 68].

Fractals are patterns (spatial or temporal), which display statistical self-similarity, that is, where the statistical properties of the pieces are proportional to the statistical properties of the whole. In an idealized model, this property holds on all scales. The real world, however, necessarily imposes upper and lower bounds over which such scale-invariant behavior applies. An illustrative example of a temporal fractal is the analysis
of the step-to-step (stride interval) fluctuations in human walking rhythm. The stride interval has been thought to be quite regular under healthy conditions. However, subtle but complex fluctuations are apparent in healthy gait dynamics. Whereas this noise had been previously observed, until recently these fluctuations had not been characterized. Goldberger et al. [69] reported that fluctuations in the stride interval during walking are not random, but display long-range correlations, extending over thousands of steps, consistent with a fractal gait rhythm. These correlation properties evolve during childhood and degrade both with physiologic aging and with certain degenerative neurologic diseases, including Huntington’s disease and Parkinson’s disease [17].

Longstaff and Heath [70] observed fractal dimensionality in handwriting velocity components. Fernandes and Chau [66], performed a related experiment analyzing pacing and grip force data of a cyclic, ballistic drawing task and found strong evidence in both for self-affine scaling that is characteristic of fractal time-series. In that experiment, adult subjects drew circles of varying sizes and at varying rates on a digitizing tablet, using a pen instrumented with grip sensors to additionally measure radial force applied to its barrel. Subjects also drew circles in synchrony with a metronome. When the subjects were required to synchronize their drawing with a metronome, fractal dynamics for drawing period decreased, while those for grip force did not. This result indicated that independent processes control the variations in pacing and grip force.

The research described above led to the desire to explore whether or not abnormalities exist in the fractal dynamics of the drawing movements of children with ASD and whether timing deficits are apparent in continuous or discontinuous timing tasks. In addition, the following study describes the relationship between spatial characteristics and kinetic variables in a simple graphomotor activity in children with ASD.
Chapter 3

Statistical persistence and timing characteristics of repetitive circle drawing in children with ASD

Chapter 3 addresses the primary objectives of this thesis. In this chapter, the fractal dimension of a cyclic drawing task is determined and compared between typically developing children and children with ASD. Timing variability in continuous and discontinuous drawing tasks is also quantified.

Note: Section 3.2 contains some repeated background information and parts of the methodology described in section 3.3 are outlined again in section 4.3.
3.1 Abstract

Autism spectrum disorder (ASD) is a pervasive neurodevelopmental disorder associated with social communication deficits and repetitive behaviors/restrictive interests. Sensory motor deficits, although not part of the diagnostic criteria for the disorder, constitute frequently reported symptoms. Many standardized tests exist to characterize motor difficulties and various studies have used these standardized tests to assess movement difficulties in ASD. These measures evaluate motor output and performance, but they do not provide any information about the underlying dynamics that produce movement. The objective of this research is to study the temporal dynamics of an approximately periodic motor activity (circle drawing) in children with ASD. The natural rhythm of periodic motor activities such as human gait and circle drawing are known to exhibit statistical persistence in typically developing individuals.

For the purposes of this study, a sample of children aged 4 to 8 years, with a primary diagnosis of ASD, were asked to draw circles using a computerized tablet and pen, which record spatio-temporal data. Participants were asked to draw circles with both hands separately at their preferred pace, both continuously and discontinuously, and then as fast as they could. Using the tablet data, we were able to assess fractal dynamics and global temporal dynamics such as mean and coefficient of variation. These estimated quantities were then compared to those of typically developing controls.

No difference in statistical persistence was found between children with ASD and typically developing children, suggesting that the neurobiology responsible for generating these robust fractal patterns is preserved in this population, despite known motor abnormalities. Global temporal measures showed increased variability in the ASD population in the discontinuous task only.
3.2 Introduction

Autism spectrum disorder (ASD) refers to a group of pervasive neurodevelopmental disorders. These disorders are characterized by varying degrees of impairment in communication skills, social interactions, and restricted, repetitive and stereotyped patterns of behavior [71]. The pervasive nature of ASD makes it difficult to pinpoint a single cause or mechanism, and instead diagnosis is based on a battery of qualitative behavioral tests. Various studies have been done to identify potential biomarkers for ASD, including motor development tests [24], metabolic studies [25], environmental susceptibility [26] and tests for specific genetic markers [27]. These studies provide promising research into early physiological biomarkers for ASD, but behavioral tests still dominate the diagnostic landscape. Although observed in a majority of cases, motor difficulties are not currently a criterion for diagnosis; reports of the specific nature of these motor difficulties are inconsistent.

While many tools exist to characterize motor impairments, standardized clinical tests evaluate motor output and performance but they do not provide any information about the underlying dynamics that produce movement [5]. Knowledge of these dynamics is critical to the development of targeted treatments of motor impairments. In this light, computer-based techniques have been proposed as a complement to standardized clinical tests. Computer-based techniques can provide measurement and analysis of dynamic characteristics (such as velocity, consistency, and pressure) of fine motor control. Two specific areas where computer-based techniques have been used frequently are the analyses of drawing and handwriting. These motor skills result from the interaction of sensory-motor, perceptual, and cognitive processes [6, 72, 73], and are often impaired in the presence of developmental disorders. Therefore, previous analyses of the dynamic features of drawing and handwriting have characterized impairments of these processes with the goal of aiding diagnosis or elucidating the biological etiology of impairment. For example, various works have shown a significant difference in dynamic features be-
between proficient and non-proficient handwriters [5, 7, 8, 74, 75]. Using a digitizing tablet, Rueckriegel et al. [51] delineated the normal development of several kinematic and kinetic parameters of fine motor movement (speed, automation, variability, and pressure) and determined the influence of gender, handedness and extracurricular training on drawing and writing. Computer-based techniques can be a valuable tool in analyzing the dynamic characteristics of drawing and writing tasks.

In his original description of autism, Asperger reported motor incoordination and handwriting impairments in a number of subjects [30]. Several studies have since investigated handwriting and fine motor impairments in children with ASD. For example, in a comparison of individuals with ASD against those with learning disabilities (LD), Miyahara et al. [31] found that both groups performed poorly in tests of manual dexterity. Macrographia (abnormally large handwriting) has been observed among subjects with ASD when their handwriting was compared against that of age and IQ matched controls [32].

Studies of gait and reaching/grasping have provided evidence of gross motor difficulties in ASD as well, but the available data are inconsistent. A small study by Hughes [14] showed qualitative impairment in the “reach, grasp, and place” task indicating motor planning deficits for goal directed sequences. In a kinematic study, the “reach and grasp” movement in children with autism was compared to the same movement in healthy controls. Abnormalities similar to those observed in Parkinson’s disease were noted in the speed of different phases of the movement, possibly implicating the basal ganglia [15]. This finding was consistent with an earlier kinesiologic study of gait in children with autism that reported abnormalities in stride length, stance time, hip flexion and knee extension, resembling the gait of adults with Parkinson’s [16]. Deficits in anticipatory postural adjustments were identified in children with autism by Schmitz et al. [28]. Together, these studies indicate that differences in movement patterns in ASD appear to be related to the speed and timing of different phases of movement.
Control and production of timed and coordinated movements are important aspects of skilled motor behaviour [57]. As such, timing processes in motor control have been extensively studied [58–61]. Robertson et al. [58] and later Zelaznik et al. [57] found no significant correlation between finger tapping and continuous circle drawing tasks, indicating that at least two different timing processes are used in motor control. The authors characterized circle drawing as a continuous (or emergent) task, and tapping as a discontinuous (or event-based) task. A common method for the investigation of timing mechanisms in motor tasks is to study the capacity of the motor system to produce precisely timed repetitions in periodic motor tasks, such as repetitive finger tapping or circle drawing. Timing precision in such repetitive movements is measured by the variability in intervals between motor acts (e.g. inter-tap intervals in finger tapping or cycle durations in circle drawing). When any two tasks engage a common timing process, temporal precision (variability) on one task is predictive of precision on the other [76]. Exploiting this predictive relationship between tasks, finger-tapping, discontinuous circle drawing, and temporal duration discrimination (all event-based timing tasks) were shown to engage the same timing process whereas continuous circle drawing (an emergent timing task) evoked a different timing process [57–59, 63, 65, 77]. Previous studies have reported changes in circle drawing behavior and timing between the ages of 4–10 and have generally concluded that mastery of these tasks is complete at approximately 9–10 years old, at which point children draw circles in a fashion very similar to adults [51]. Studies investigating the developmental trajectory of circle drawing and similar activities have focussed on children in the age range of 4–8 years [54–56]. The works of Ivry et al. [62] and Spencer et al. [59] showed that the timing variability in a continuous circle drawing task is not affected in patients with cerebellum dysfunction, however timing of an event-based task is affected, indicating that event-based timing relies to some level on the cerebellum.

Interestingly, as a potential explanation for many of the motor abnormalities observed in ASD, many studies point to differences in the cerebellum [35] and the basal ganglia [15]
in children with ASD, since both are involved to some degree in movement coordination and planning. Several studies have identified structural differences in the cerebellum of children with ASD compared to typically developing controls, but the data are inconclusive. Older studies looked at the cross-sectional area of the cerebellum, while more recent studies have analyzed the volume. In both cases, some papers report reduced cerebellar volume in specific regions [36–41, 46–48], while others report no differences [42–45, 49].

Temporal precision (variability) has been previously measured using the coefficient of variation. This approach assumes that timing variations are uncorrelated between cycles. Contradicting this assumption, long-term correlations or statistical persistence (fractal patterns) have been reported in time series of repetitive circle drawing cycle times [66], finger-tapping intervals [67], and stride intervals in human gait [17, 61, 68]. Longstaff and Heath [70] observed fractal dimensionality (statistical persistence) in handwriting velocity components. Fernandes and Chau [66] found strong evidence of self-affine scaling, characteristic of fractal time-series, in both pacing and grip force data of a cyclic, ballistic drawing task. In that experiment, adult subjects drew circles of varying sizes and at varying rates on a digitizing tablet, using a pen instrumented to measure radial force applied to its barrel. Subjects also drew circles in synchrony with a metronome. In this condition, statistical persistence diminished for drawing period but not for grip force fluctuations. Fractal patterns are often thought to be indicative of a healthy physiological system, and previous studies of human gait indicate that long-term correlations in stride intervals are altered in diseases such as Parkinson’s [69] and Huntington’s [17]. Fractal patterns of gait have also been shown to change with age, evolving during childhood and degrading with aging [17, 78].

In light of this previous research, we have examined whether or not abnormalities exist in the temporal dynamics of the drawing movements of children with ASD. Based on previous research comparing movement patterns in individuals with ASD to those observed in individuals with Parkinson’s, we expected children with ASD to exhibit
altered temporal dynamics. We also expected a lower timing precision in children with ASD for event-based tasks as these rely on the cerebellum. To verify these hypotheses, we examined long-term correlations and timing statistics of circle drawing under several conditions in children 4-8 years of age with and without ASD.

### 3.3 Methods

#### 3.3.1 Participants

Twenty-three children with ASD and twenty typically developing children between the ages of 4 and 8 years (3 female in each group) were recruited. Individuals with ASD met DSM-IV criteria on the basis of a clinical interview, the Autism Diagnostic Interview – Revised (ADI-R) and the Autism Diagnostic Observation Schedule (ADOS). Participants diagnosed with a genetic or metabolic disorder known to be associated with autism were excluded (e.g., fragile-X, tuberous sclerosis). Participants had normal or corrected-to-normal vision, and were not using any medication which may have affected motor function.

Based on scores from the Stanford-Binet Intelligence Scales (5th edition), all participants had a full scale IQs (FSIQ) above 70. However, previous literature indicates that task-specific measures of intelligence may be more appropriate for use in matching in children with ASD [33, 79]. Therefore, the non-verbal IQ (NVIQ) was used as the primary intelligence measure for analysis. Non-verbal IQ was also thought to be a more appropriate measure since the study included a motor timing task with little verbal input. Informed written consent from a legal guardian was obtained for each participant, while assent was obtained from each child. The research protocol was approved by the institutional research ethics board.
### 3.3.2 Experimental Apparatus

Data for the drawing task were collected using a Wacom Cintiq 15x digitizing tablet and pen (see Figure 3.1). The pen was instrumented with an array of TekScan model 9811 force sensors on its barrel, as outlined in Chau et al. [8]. These sensors measure the grip force applied radially to the pen barrel by the user’s hand. Forces were sampled at a frequency of 250 Hz using the USB-6210 DAQ card from National Instruments in conjunction with custom circuitry, a modified Tekscan interface box and custom data collection software. The horizontal \((x)\) and vertical \((y)\) position of the pen on the tablet, as well as the axial force exerted on the tablet at the pen tip, were recorded at a sampling rate of 142.8 Hz using a custom developed C++ program.

![Digitizing tablet and grip sensing pen](image)

**Figure 3.1:** Digitizing tablet and grip sensing pen

### 3.3.3 Experimental Protocol

Six different circle drawing conditions (refer to Table 3.1) were tested in a randomized order. Each condition was explained and demonstrated before the protocol began. Participants were given an opportunity to practice all conditions before testing began to verify their understanding of the conditions. Participants were seated comfortably and asked to draw circles on the tablet, following a 10 cm circle template. Between each
session, participants were given an optional resting period as needed.

Participants who did not have an IQ test on record were administered the Stanford-Binet Intelligence Scale (5th edition), an assessment designed to measure intellectual abilities in individuals across a wide age range and developmental ability. The assessment takes approximately 2 hours.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Condition</th>
<th>Circle drawing instructions</th>
<th>Time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant</td>
<td>Continuous</td>
<td>Continuously at subject’s preferred rate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Discontinuous</td>
<td>Discontinuously at subject’s preferred rate</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>Continuously “as fast as you can”</td>
<td>1</td>
</tr>
<tr>
<td>Non-dominant</td>
<td>Continuous</td>
<td>Continuously at subject’s preferred rate</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Discontinuous</td>
<td>Discontinuously at subject’s preferred rate</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Fast</td>
<td>Continuously “as fast as you can”</td>
<td>1</td>
</tr>
</tbody>
</table>

### 3.3.4 Data Analysis

**Data Processing**

Pen position on the tablet was used to determine the period for drawing a circle. A period was defined as the time elapsed between the maximum vertical extents of two consecutive circles [65]. Figure 3.2 illustrates an example of the y position time series, and its corresponding extracted cycle durations. Occasionally, a participant would pause for a few seconds while drawing or would change circling direction, therefore circles where the pen was removed from the page were discarded from analysis. Longstaff and Heath [70] have demonstrated that removing short segments of a time-series in this manner does not adversely affect the measurement of fractal scaling.

**Temporal Analysis**

The mean and coefficient of variation of circle drawing period are calculated for each participant for each of the six drawing conditions. Summary statistics of drawing time
Fractal Analysis

Plots of power spectral density (PSD) and root-mean-squared (RMS) fluctuations were constructed for the self-paced condition for each participant to show fractal scaling trends.

To facilitate comparison with previous literature on circle drawing [66], the Hurst coefficient, $H$, a measure of statistical persistence in a time series, was estimated in 2 different ways as described below. Note that $0 < H < 1$ and that $H = 2 - D$ for fractional Brownian motion (fBm), where $D$ is the fractal dimension, while $H = \alpha$ for fractional Gaussian noise (fGn), where $\alpha$ is the fractal scaling exponent. Recall that fBm signals are nonstationary while fGn signals are stationary.

The first estimate, $H_{df}$, of the Hurst coefficient was based on detrended fluctuation analysis [80]. The signal was divided into intervals of width $n$ and the average fluctuation $F(n)$ around a piece-wise linear least-squares fit was computed. The fluctuation measure was recalculated for several different values of $n$. The slope of the line through the points on a log($F(n)$) versus log($n$) plot yielded the fractal scaling exponent $\alpha$, which served
as the estimate, $H_{dfa}$, of the Hurst exponent. This estimate is popular in physiological literature [80].

For the second estimate, $H_{pref}$, of the Hurst coefficient, the signal was first classified as either fBm or fGn according to a discriminant value, $H'$, obtained using the signal summation conversion (SSC) method [81]. The SSC method computes the discriminant, $H'$, for the time series. If $H' < 0.8$, then the signal was considered fGn, and $H_{pref}$ was determined using the dispersional analysis method [82]. If $H' > 1$, then the signal was classified as fBm, and $H_{pref}$ was computed with the bridge-detrended, scaled windowed variance method [83]. If $H'$ fell between 0.8 and 1, then the algorithm was unable to classify the signal, and $H_{pref}$ was obtained via the DFA method.

While $H_{pref}$ may be more precise than $H_{dfa}$ in some situations, its systematic error may vary discontinuously with fractal dimension [84]. This occurs since systematic error depends on both the method and the signal characteristics, and one of three different methods can be used to calculate $H_{pref}$ [84]. Since the differences between Hurst coefficients are reported, we must be concerned that the systematic errors in estimating $H_{pref}$ may have introduced a false treatment effect. For this reason, all statistical analyses have also been run on the Hurst coefficients estimated solely by the DFA method.

Since physiological signals often lie on the boundary between fGn and fBm signals, we report values of $H'$ rather than the Hurst coefficient, $H$. For fGn signals, $H' = H$, and $0 < H' < 1$. For fBm signals, $H' = H + 1$, and $1 < H' < 2$. The domain of $H'$ therefore includes both classes of signals.

**Statistical Analysis**

Linear regression was used to assess the effects of participant group (i.e. ASD vs typically developing) on the temporal dynamics of fine motor activity. Models looked separately at group differences in $H_{dfa}$, $H_{pref}$, mean circle drawing time and CV for each task, taking into account the co-variates of age, gender, and NVIQ. By looking at the $group \times condition$
interaction for each outcome measure, we were able to determine whether or not any of the outcome measures for each condition were significantly different between groups. By examining the \( \text{group} \times \text{age} \) interaction, it was also possible to estimate whether or not developmental patterns were significantly different between groups. A Bonferroni correction was used to account for multiple comparisons, yielding an adjusted significance level of 0.017. A Levene test for unequal variances was used to compare whether the variability of each timing parameter was significantly different between groups.

3.4 Results

A total of 15 children with ASD and 19 typically developing (TD) children were included in the analysis. Several children were excluded because they failed to complete the assessment (5 with ASD and 1 TD), and because the tested FSIQ was below the cutoff of 70 (3 with ASD). Age, NVIQ, and gender were all included in the regression model. Summary statistics (mean and standard deviation where appropriate) for these variables in each group are shown in Table 3.2.

Table 3.2: Participant characteristics for the autism (ASD) and typically developing (TD) groups. The last column indicates p-values from a t-test between groups.

<table>
<thead>
<tr>
<th></th>
<th>ASD</th>
<th>TD</th>
<th>( p )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>6.80 ± 1.59</td>
<td>5.25 ± 1.00</td>
<td>0.002</td>
</tr>
<tr>
<td>Full-scale IQ (FSIQ)</td>
<td>94.8 ± 15.7</td>
<td>115.3 ± 8.54</td>
<td>0.0003</td>
</tr>
<tr>
<td>Non-verbal IQ (NVIQ )</td>
<td>99.7 ± 18.9</td>
<td>116.5 ± 9.47</td>
<td>0.002</td>
</tr>
<tr>
<td>Gender (male:female)</td>
<td>11:4</td>
<td>11:8</td>
<td></td>
</tr>
<tr>
<td>Handedness (right:left)</td>
<td>13:1</td>
<td>18:1</td>
<td></td>
</tr>
</tbody>
</table>

3.4.1 Timing Variability

The results of regression analysis on mean circle drawing time and coefficient of variation (CV) are summarized in Table 3.3. No differences were observed between hands \( (p = 0.8) \), and therefore the reported values include data from both hands. Mean circle drawing
Table 3.3: Statistics for mean circle drawing period. Results for each group are reported as Mean (95% Confidence Interval: Lower, Upper), and group difference as TD minus ASD (95% CI: Lower, Upper). Results approaching a significance level of 0.017 are indicated with *.  

<table>
<thead>
<tr>
<th>Measures</th>
<th>Continuous</th>
<th>Discontinuous</th>
<th>Fast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASD</td>
<td>0.83 (0.63, 1.03)</td>
<td>1.22 (1.01, 1.43)</td>
<td>0.57 (0.37, 0.77)</td>
</tr>
<tr>
<td>TD</td>
<td>0.69 (0.52, 0.87)</td>
<td>1.48 (1.31, 1.65)</td>
<td>0.49 (0.32, 0.66)</td>
</tr>
<tr>
<td>Difference</td>
<td>-0.14 (-0.44, 0.17)</td>
<td>0.26 (-0.051, 0.56)</td>
<td>-0.084 (-0.39, 0.22)</td>
</tr>
<tr>
<td>p</td>
<td>0.34</td>
<td>0.10</td>
<td>0.58</td>
</tr>
<tr>
<td>CV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASD</td>
<td>0.70 (0.54, 0.86)</td>
<td>0.90 (0.73, 1.06)</td>
<td>0.43 (0.27, 0.58)</td>
</tr>
<tr>
<td>TD</td>
<td>0.58 (0.45, 0.71)</td>
<td>0.61 (0.48, 0.75)</td>
<td>0.45 (0.32, 0.59)</td>
</tr>
<tr>
<td>Difference</td>
<td>-0.12 (-0.36, 0.11)</td>
<td>-0.28 (-0.52, -0.044)</td>
<td>0.027 (-0.21, 0.26)</td>
</tr>
<tr>
<td>p</td>
<td>0.30</td>
<td>0.021*</td>
<td>0.82</td>
</tr>
</tbody>
</table>

time was not significantly different between groups for any of the conditions, however CV was found to be different between groups for the discontinuous condition ($p = 0.021$). This result would be statistically significant with an alpha value of 0.05, but does not pass the more stringent value of 0.017 used to account for multiple comparisons. In addition, age appears to have a similar effect on each group, showing no significant results for the $group \times age$ interaction ($p = 0.5$).

Increased variability in CV was also observed within the ASD group (confirmed with a Levene test for unequal variances ($p < 0.001$)). However, because CV appears to be related to NVIQ, we had to determine if this increased variability was entirely accounted for by a wider spread in IQ. A model was created which controlled for NVIQ, age, and gender, from which the residuals were determined for each group. Residuals represent the differences between the observed data and the predicted value for a given NVIQ. If the variability was truly higher for the ASD group, then we would observe higher residuals than those for the typically developing children. Residuals were compared using a two sample t-test, which showed no difference in residuals between groups ($p > 0.99$). The increased variance, therefore, was completely accounted for by increased IQ variance in the ASD group.
3.4.2 Long-term Correlations

The power spectral density for the inter-event time series exhibited power-law scaling over more than two decades for all participants. Figures 3.3(a) and 3.3(b) show representative PSD log-log plots for one child from the ASD group and one typically developing child. Both log-log plots exhibit an approximately linear decay in spectral power at increasing frequencies.

![Log-log plots for ASD and TD](image)

Figure 3.3: Plot of power spectral density (PSD) for (a) one child with ASD and (b) one who is typically developing.

RMS fluctuations also showed power-law scaling as a function of window size, allowing the estimate of the Hurst coefficient for the self-paced conditions by DFA. Figure 3.4 shows the results of DFA for the same participants shown in Figure 3.3.

In general, both groups exhibited long-range correlations in their mean circle drawing time ($H_{df_a} > 0.5$). The results for $H_{df_a}$ and $H_{pref}$ are summarized in Table 3.4. The Hurst coefficients measured by the two methods were statistically similar ($p = 0.8$). Regression revealed no difference in $H_{df_a}$ or $H_{pref}$ between the ASD and TD groups ($p = 0.7$ and $p = 0.5$, respectively). Values of $H$ appear to be unaffected by the particular motor deficits observed in children with ASD.
Figure 3.4: Log-log plot showing the determination of $H_{dfo}$ for (a) one child with ASD and (b) one who is typically developing.

Table 3.4: Statistics for statistical persistence of circle drawing time. Results for each group are reported as Mean (95%CI: Lower, Upper), and group difference as TD minus ASD (95%CI: Lower, Upper).

<table>
<thead>
<tr>
<th>Measure</th>
<th>$H_{dfo}$</th>
<th>$H_{pref}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASD</td>
<td>0.74 (0.64, 0.84)</td>
<td>0.81 (0.64, 0.98)</td>
</tr>
<tr>
<td>TD</td>
<td>0.71 (0.62, 0.79)</td>
<td>0.72 (0.58, 0.87)</td>
</tr>
<tr>
<td>Difference</td>
<td>-0.03 (-0.19, 0.13)</td>
<td>-0.09 (-0.35, 0.17)</td>
</tr>
<tr>
<td>$p$</td>
<td>0.7</td>
<td>0.5</td>
</tr>
</tbody>
</table>

### 3.5 Discussion

#### 3.5.1 Timing Variability

No difference was observed in the mean circle drawing time between groups ($p = 0.9$) but the coefficient of variation revealed group differences in the discontinuous condition ($p = 0.021$). These results were not statistically significant with the more stringent alpha value of 0.017, but represent a likely difference between groups that should be confirmed with further research with a larger sample size. Coefficient of variation is often used to characterize timing precision, and based on previous results of other discontinuous timing tasks in children with ASD, we expected to see decreased timing precision in this condition [85]. Our results indicate that increased variability was observed in self-paced, discontinuous...
uous timing tasks, even where participants were not provided with explicit instructions to ensure consistent timing. Based on the literature, there are at least two potential explanations for this increased variability, one which attributes increased variability to immature limb dynamic control [63], and one which draws on cerebellar differences to explain discrepancies [85].

Previous research investigated whether temporal consistency during circle drawing may result from the processes that control parameters related to trajectory formation (e.g., muscle stiffness) and not those related to timing control. For example, continuous circles with constant curvature can be produced by keeping a constant tangential velocity, without input from any sort of central timing mechanism [77]. Bo et al. [63] observed a significant difference between the age effects in continuous and discontinuous circle drawing. They attributed part of this difference to age-related development of limb dynamic control as dynamic demands for discontinuous circle drawing are more complex than those of continuous circle drawing, involving more acceleration and deceleration. The results of the present study do not support this hypothesis since we did not find a significant difference in regression slopes between self-paced continuous and discontinuous tasks even though there were differing kinematic demands. CV decreased with age in both conditions, but with a similar trajectory ($p = 0.8$). Bo et al. [63] also implicated cerebellar control and maturation as an additional explanation for their results.

A different explanation, drawing on cerebellar differences, is supported by previous studies observing differences in discontinuous timing tasks in individuals with ASD [85]. Sheridan and Mcauley [85] attributed the difference in timing precision between children with ASD and age-matched controls in discontinuous tasks to increased clock variance based on the two stage model of timing proposed by Wing and Kristofferson [86]. Along with the results of Sheridan and Mcauley [85], our current results lend additional support to the findings of Ivry and Keele [87], in which patients with cerebellar lesions showed increased variability in discontinuous timing tasks. Both the cerebellum and the basal
ganglia (where differences have been observed in the brains of children with ASD [15, 35]) are involved to some degree in movement coordination and planning, with the cerebellum thought to be primarily responsible for regulating discontinuous timing tasks. Children with ASD have known cerebellar differences which seem to affect their ability to produce consistently timed intervals in a self-paced, discontinuous drawing task. Further research is required to determine if these findings are specifically age-related or whether the same is true in adulthood.

### 3.5.2 Long-term Correlations

Mean circle drawing time for the typically developing children showed strong evidence of statistical persistence, characteristic of fractal time-series. To our knowledge, this is the first reported evidence of statistical persistence of a circle drawing task in children. The presence of statistical persistence is consistent with results showing persistence in a similar drawing task in adults [66], however Hurst coefficients appear to be lower than those previously observed in adults ($H_{\text{pref}} = 0.84 \pm 0.24$ in children as opposed to an average $H_{\text{pref}} = 1.03 \pm 0.15$ in adults). These results suggest a developmental trajectory similar to that observed in gait [78], with fractal dynamics gradually moving towards the adult value with maturity of the motor system, and degrading with aging and disease.

In spite of observed motor difficulties, children with ASD appear to have maintained long range correlations in fine motor activity, also showing strong evidence of statistical persistence. Values of $H_{\text{pref}}$ and $H_{dfa}$ were found to be equivalent between the TD and ASD groups ($p = 0.5$ and $p = 0.7$, respectively). Differences between point estimates for each group were extremely small ($0.09$ for $H_{\text{pref}}$ and $0.03$ for $H_{dfa}$) and confidence intervals for these estimates overlapped significantly between groups. While significant overlap strongly suggests a lack of difference between the groups, maximum estimated difference between groups (as defined by the difference confidence intervals) should ideally rule out a clinically significant difference. Research in statistical persistence of fine mo-
tor activity in populations with motor impairments is limited, and therefore, estimates of values which might represent a clinically significant difference are largely based on gait data, where a wide body of research exists characterizing impaired dynamics. Gait studies generally report differences in $H_{df}$ of approximately 0.2-0.3 between healthy and pathological populations [17, 18, 78]. If we extend these results to fine motor activity, confidence limits for the difference between groups (see Table 3.4) may rule out a clinically significant difference, but replication of these results with a larger sample size is recommended to confirm the lack of difference.

Despite the small sample size, both groups fall into the category of “statistical persistence” ($0.5 < H_{df} < 1$), indicating that the ability to produce long range correlations in a continuous timing task is maintained in children with ASD. These results are supported by previous evidence indicating that timing deficits in ASD are caused by cerebellar differences, and continuous timing has been shown to be unaffected in individuals with cerebellar lesions [87]. Future research might look at statistical persistence in a discontinuous task in this population to determine if the results parallel those found in timing variability for discontinuous tasks in this population (as discussed above).

3.6 Conclusions

The present study investigated motor difficulties in ASD in the context of a self-paced circle drawing activity. For each task, we examined the nature of statistical persistence in the mean circle drawing series (measured by the Hurst coefficient), and timing variability (measured by the coefficient of variation of circle drawing times). While no differences were observed in the Hurst coefficient between groups, a difference between groups was seen in the coefficient of variation in the discontinuous task only. Our results support the hypothesis that children with ASD have an intact ability to consistently produce continuous movements, but increased variability in production of discontinuous movements.
This is true even when children are given no specific instructions to ensure consistent timing. Consistent timing is an important aspect of motor control, and an increased understanding of motor deficits in the ASD population could lead to better treatments and more targeted interventions. Future research should examine fractal dynamics of discontinuous circle drawing in this population.
Chapter 4

Spatial and kinetic characteristics of repetitive circle drawing in children with ASD

Chapter 4 specifically addresses the secondary objectives of this thesis. In this chapter, we describe the relationship between spatial and kinetic aspects of a circle drawing task in children with ASD. Results are compared to children who are typically developing and differences are quantified.

Note: Section 4.2 contains information repeated from the background in Chapter 2 and section 3.2. The study protocol has been previously outlined in section 3.3.
4.1 Abstract

Autism spectrum disorder (ASD) refers to a group of neurodevelopmental disorders associated with social communication deficits and repetitive behaviors. While motor difficulties are not a criteria for diagnosis, they are noted in many patients, along with a variety of sensory perception and processing deficits. Differences have been observed in visual perception, visual-motor integration, and fine motor skills, all of which contribute significantly to writing and drawing proficiency. As a result, handwriting is known to be poor in this population. Research, however, is divided on the specific nature of handwriting difficulties in ASD, as well as the specific causes. Some studies have observed macrographia, while others indicate that letter formation is problematic in ASD. The level of cognitive demands also plays a role, with study results often depending on the complexity of the task. It is also unclear whether visual perception, fine motor difficulties, or visual-motor integration plays the largest role in handwriting difficulties.

We attempted to study various quality characteristics of continuous circle drawing traces (such as area, centroid location, eccentricity, and orientation), as well as kinetic motor parameters of these drawing movements in children with ASD. A simple repetitive circle drawing task was administered to 15 children with ASD and 19 typically developing children between the ages of 4 and 8 years. Quality parameters as well as kinetic process variables were compared between groups.

No differences were observed in any of the quality measures, however children with ASD exhibited increased variability in axial force, and decreased mean grip force. These results suggest differences in modulation of grip and axial forces in order to maintain quality and fluency in the pen trace. Understanding the specific nature of motor deficits is the first step towards developing targeted treatment for these impairments. Future studies should extend these results to handwriting analysis to facilitate interventions which could improve graphomotor skills.
Chapter 4. Spatial-kinetic drawing analysis in children with ASD

4.2 Introduction

Autism spectrum disorder (ASD) is a group of neurodevelopmental disorders, clinically characterized by impairment in three core areas: a) communication skills; b) social interactions; and c) restricted, repetitive and stereotyped behaviors, interests or activities (DSM-IV). In addition to these core deficits, ASDs are also associated with impairments in other domains. For example, ASD is associated with atypical patterns in visual perception [1], visual-motor integration [2, 3], and fine motor skills [4].

Motor difficulties, in particular, are highly prevalent in individuals with ASD, although these difficulties do not constitute a diagnosis criterion. Motor impairments have been reported both in gross and fine motor function. Studies of gait and reaching/grasping have provided evidence of difficulties related to the coordination and timing of certain phases of movement [14–16].

Impairments in fine motor function have been reported widely in ASD [88]. Specifically, standardized tests of motor development, such as the Movement Assessment Battery for Children (M-ABC), have revealed impairments of fine motor skills in children with ASD relative to population norms [4], as well as impairments in manual dexterity in children with Asperger’s [89]. Moreover, Noterdaeme et al. [90] observed deficits in upper limb function using the standardized grooved pegboard task, an indication of motor coordination and speed. The grooved pegboard task has been extensively studied in children with ASD, with results consistently confirming the deficits observed in children with ASD on motor coordination and speed [20, 91–93]. Noterdaeme et al. [90] also observed deficits in upper limb function in skills such as drawing and cutting.

An important functional skill affected by fine motor impairment is graphomotor ability (e.g., drawing and handwriting). Impairments in graphomotor skills are of special concern due their significant impact on academic performance, communication, and self-esteem [29]. Graphomotor difficulties are highly prevalent in ASD [88], though the nature of these difficulties is not well understood. In his original description of autism, Asperger...
noted motor incoordination and handwriting impairments in a number of children [30]. Recent studies have further characterized the specific nature of graphomotor impairments in children with ASD. According to one report, individuals with autism spectrum disorder tended to exhibit macrographia (abnormally large handwriting) compared to age- and IQ-matched controls [32]. Children with ASD also performed poorly on the Minnesota Handwriting Assessment compared to controls [33]. More specifically, the study found that children with ASD had poorer quality of letter formation but were comparable to controls in their ability to correctly size, align, and space their letters, contrary to earlier reports [32] of macrographia in children with ASD. Although there is much disagreement about handwriting impairments in ASD, studies seem to agree that children with ASD have difficulties with letter formation [33, 94, 95].

Studies of graphomotor abilities in children with ASD have fixated almost exclusively on outcome measures related to the written product [88]. Many of the standardized clinical tests used with children with ASD evaluate graphomotor output and performance, but they do not provide any information about the underlying dynamics that produce movement [5]. Handwriting and drawing, however, are inherently dynamic processes that involve an intricate interplay of biomechanical mechanisms over time. To study this dynamic nature of motor performance, computer-based techniques using a force sensitive tablet [6, 7], and most recently force-sensitive writing utensils [8–11], have been proposed as a complement to standardized clinical tests for analyzing graphomotor skills. These techniques provide measurement and analysis of dynamic characteristics, such as velocity, consistency, and pressure of fine motor control. Various authors have distinguished between typically developing children and those with cerebral palsy [8], developmental coordination disorder [96, 97], and attention hyperactivity disorder [98], on the basis of kinetic and kinematic variables of handwriting. Previous studies have also suggested a strong correlation between grip and axial forces [8, 99].

The dynamic nature of graphomotor abilities has not been investigated in ASD. How-
ever, there is emerging evidence suggesting that ASD may be associated with atypical biomechanical control in graphomotor tasks. In particular, ASD is associated with varying degrees of impairment in organization, planning and execution of movement [12, 13] which affect control of writing or drawing instruments. Compromised kinetic control, due for example to hypotonia [19] and weak grip strength [20] can affect the effort required to hold a pen and therefore the quality of writing over time [21]. Coordination of grip and load forces, essential for control and quality of writing [21], has also been shown to be impaired in children with ASD [22]. To further the understanding of the biomechanical underpinnings of graphomotor difficulties in ASD, the present study investigated the kinetic characteristics of a graphomotor task using a digitizing tablet and force-sensitive pen. This study focused on children, as children with ASD are known to learn to compensate for deficits in motor control [100], therefore it may be interesting to probe differences in fine motor skills while the skills are still developing and differences may be more apparent. Differences in dynamics observed in young children may also aid in early intervention and targeted treatment of motor impairments [5].

Complicating the evidence regarding graphomotor difficulties in ASD is the fact that findings appear to be highly dependent on the nature of the task and the level of cognitive involvement. For example, in handwriting studies, reported values of a letter size metric have varied depending on whether the writing task involved verbal memory recall [32], dictation [94], or copying [33, 101]. Handwriting legibility has correlated well with verbal memory and spelling [94], suggesting that tasks engaging these higher level processes may unveil group differences unrelated to fine motor activity specifically. In addition, children with ASD seem to perform poorly on tests of visual-motor integration involving pen and paper [91, 102, 103], while they perform well on other visual-motor integration tasks (such as the Block Design or Object Assembly subtasks in the Wechsler Intelligence Scales [103]).

A simple age-appropriate drawing task with minimal cognitive and language com-
ponents might therefore be conducive to pinpointing specific fine motor difficulties in children with ASD. One such a task that is widely used in studies of motor control is circle drawing [51–53, 55]. Circles are relatively simple shapes that emerge very early on in the drawings of young children. Children can distinguish perceptually between circles and other shapes by their first birthday and can reproduce circular shapes at approximately 3 years old [50]. This is one of the first shapes to be acquired and is mastered at a young age compared to more difficult shapes such as triangles and squares [51]. It is therefore a suitable task for drawing studies involving young children.

In light of previous research, we attempted to study various quality characteristics (such as area, centroid location, eccentricity, and orientation) of circle drawing traces, as well as kinetic parameters of drawing movements in children with ASD. Quality of letter formation has been shown to be impaired in children with ASD in handwriting studies, however given that circle drawing is mastered early in development, we hypothesized that quality outcomes would be comparable between children with ASD and their typically developing peers. Based on previous research indicating deficits in coordination of grip and load forces [21], we expected differences in kinetic movement parameters, specifically in the relationship between grip and axial forces used during drawing. Since children with ASD are known to exhibit abnormal brain lateralization and a decreased hand preference [104, 105], we tested both hands in order to make comparisons.

4.3 Methods

4.3.1 Participants

Twenty-three children with ASD and twenty typically developing children between the ages of 4 and 8 years (3 female in each group) participated in the study. Individuals with ASD met DSM-IV criteria on the basis of a clinical interview, the Autism Diagnostic Interview – Revised (ADI-R) and Autism Diagnostic Observation Schedule (ADOS).
Participants diagnosed with a genetic or metabolic disorder known to be associated with autism were excluded (e.g., fragile-X, tuberous sclerosis). Participants had normal or corrected-to-normal vision, and were not using any medication which may have affected motor function (e.g. atypical antipsychotics, stimulants). Informed written consent from a legal guardian was obtained for each participant, while assent was obtained from each child. The research protocol was approved by the institutional research ethics board. Based on scores from the Stanford-Binet Intelligence Scales (5th edition), all participants had a full scale IQ (FSIQ) above 70.

4.3.2 Experimental Apparatus

Data for the drawing task were collected using a Wacom Cintiq 15x digitizing tablet and pen (see Figure 4.1). The pen was instrumented with an array of TekScan model 9811 force sensors on its barrel, as outlined in Chau et al. [8]. These sensors measured the grip force applied radially to the pen barrel by the user’s hand. Forces were sampled every 4 ms using a USB-6210 DAQ card from National Instruments in conjunction with custom circuitry, a modified Tekscan interface box and custom data collection software. The horizontal ($x$) and vertical ($y$) position of the pen on the tablet, as well as the normal force exerted on the tablet at the pen tip, were recorded at intervals of 7 ms using a custom developed C++ program.

4.3.3 Experimental Protocol

Participants completed a circle drawing task with each hand. Participants were seated comfortably and asked to draw circles continuously on the tablet for 5 minutes, following a 10 cm circle template. Participants were given resting periods as needed between sessions.

Participants who did not have an IQ test on record were administered the Stanford-Binet Intelligence Scale (5th edition), an assessment designed to measure intellectual
abilities in individuals across a wide age range and developmental ability. The assessment takes approximately 2 hours.

4.3.4 Data Analysis

Spatial Measures

Pen position on the tablet was used to segment the circles. A single circle was defined as the trace between two consecutive peaks in the y-axis (axis perpendicular to the participant [65]). Various spatial characteristics of each circle were calculated, including area, centroid location, eccentricity, orientation, and spatial fractal dimension. These measures are taken to be representative of the quality of the circle traces, with high quality circles being as close to the template circle as possible. The calculation of each measure is detailed below.

**Area** was defined by the number of pixels contained within one circle. For ease of comparison, this value was converted to $mm^2$ based on the screen resolution.

**Centroid** was taken as the centre of mass of the area. This gave the coordinates of the centroid in $x$ and $y$, from which the distance from the circle centroid to the centre...
of the template circle was calculated. The centroid offset from the centre of the template is reported in \textit{mm}.

**Eccentricity** represented the ratio of major and minor axes of an ellipse with the same second moments as the circle.

**Orientation** represented the angle (from the horizontal) of the axis of an ellipse with the same second moments as the circle. This value varied between 0 and 90°.

**Fractal dimension** was calculated by a box counting method to quantify the roughness of the circular traces. Dooijes and Struzik [106] employed a box counting method to describe the spatial fractality of handwriting traces, particularly, in its circular, looping patterns. Based on this method, the drawing area was divided into a series of boxes of varying sizes \( s_i, i = 1, ..., n \). For each box size, the number of boxes, \( N_i \), containing at least one point from the complete circle trace was counted. The box counts and box sizes are related by the equation \( N(s) = (1/s)^D \) where \( D \) is the fractal dimension. Rearranging the equation gives \( \log(N(s)) = D \log(1/s) \). Therefore we plotted \( \log(N(s)) \) vs. \( \log(1/s) \), and took the slope of the line as an estimation of \( D \).

Note that, with the exception of the fractal dimension, the spatial characteristics considered herein were estimated on a per circle basis and were thus static parameters. The mean and coefficient of variation (CV) of each spatial characteristic were calculated for each participant.

**Kinetic Analysis**

Axial force (the force of the pen tip on the tablet surface in the direction of the longitudinal axis of the pen) was recorded as a voltage and changed to a force using calibration data obtained as outlined in Chau et al. [8]. The mean and CV were then calculated. Grip force data (the force exerted on the pen barrel) were calibrated and summed over
all the sensors to produce a single grip force time series. This time series was then used to determine the mean and CV of grip force for each participant.

In addition, the cross correlation between the grip and axial force time series was determined. The axial data were first interpolated in order to match the time stamps of the grip data. The maximum correlation between the two signals was calculated, as well as the lag at which this correlation occurred. The time was noted in order to determine the offset, if any, between grip adjustments and axial adjustments, and whether this differed between groups. To assess the number of relative adjustments in grip and axial forces, the ratio of maxima in the two signals was also computed, and compared between groups.

**Statistical Analysis**

Full scale IQs (FSIQ) were used to determine if the children met inclusion criteria, however previous literature indicates that task-specific measures of intelligence may be more appropriate for use in matching in children with ASD [33, 79]. Therefore, the non-verbal IQ (NVIQ) was used as the primary intelligence measure for analysis. Non-verbal IQ was also thought to be a more appropriate measure since the study attempted to analyze a fine motor task with little cognitive or verbal impact.

Linear regression was used to assess the effects of participant group (i.e. ASD vs typically developing) on the spatial and kinetic characteristics of fine motor activity. Group differences in area, centroid location, eccentricity, and orientation, as well as axial and grip forces were separately probed using a first order regression model, taking into account the co-variates of age, gender, and NVIQ. Differences in outcome variables between groups were therefore calculated after adjusting for age, gender and NVIQ.
Table 4.1: Participant characteristics for the autism (ASD) and typically developing (TD) groups. The last column indicates p-values from a t-test between groups

<table>
<thead>
<tr>
<th></th>
<th>ASD</th>
<th>TD</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>6.80 ± 1.59</td>
<td>5.25 ± 1.00</td>
<td>0.0015</td>
</tr>
<tr>
<td>Full-scale IQ (FSIQ)</td>
<td>94.8 ± 15.7</td>
<td>115.3 ± 8.54</td>
<td>0.0003</td>
</tr>
<tr>
<td>Non-verbal IQ (NVIQ )</td>
<td>99.7 ± 18.9</td>
<td>116.5 ± 9.47</td>
<td>0.0019</td>
</tr>
<tr>
<td>Gender (male:female)</td>
<td>11:4</td>
<td>11:8</td>
<td></td>
</tr>
<tr>
<td>Handedness (right:left)</td>
<td>13:1</td>
<td>18:1</td>
<td></td>
</tr>
</tbody>
</table>

4.4 Results

A total of 15 children with ASD and 19 typically developing (TD) children were included in the analysis. Several other children recruited to the study were ultimately excluded because they either failed to complete the assessment (5 with ASD and 1 TD) or because the tested FSIQ was below the cut-off of 70 (3 with ASD). Age, NVIQ, and gender were all included in the regression model as co-variates. No differences were observed between groups based on hand used, therefore results for both hands were merged and reported together.

Summary statistics (mean and standard deviation where appropriate) for participant characteristics in each group are shown in Table 4.1.

4.4.1 Spatial Measures

Figure 4.2 shows examples of the circle traces performed by one child with ASD and one typically developing child. These plots show the wide variation in size and location within each subject, despite instructions to follow the template circle.

The results of regression analysis on spatial drawing characteristics are summarized in Table 4.2. Groups were not found to be significantly different (with an alpha value of 0.05) in any of the static spatial characteristics measured, with the exception of the variation in area, which was marginally increased in children with ASD ($p = 0.05$).
Chapter 4. Spatial-kinetic drawing analysis in children with ASD

Figure 4.2: Examples of a 5 minute circle trace for (a) one child with ASD, and (b) one typically developing child.

Table 4.2: Statistics for spatial drawing characteristics. Results for each group are reported as Mean (95% Confidence Interval: Lower, Upper). Results with $p$ values below a significance level of 0.05 are indicated with *.

<table>
<thead>
<tr>
<th>Measures</th>
<th>ASD</th>
<th>TD</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area ($mm^2$)</td>
<td>Mean 3.827 (2.299, 5.356)</td>
<td>5.123 (3.822, 6.423)</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>CV 0.90 (0.76, 1.04)</td>
<td>0.69 (0.57, 0.80)</td>
<td>0.05*</td>
</tr>
<tr>
<td>Centroid ($mm$)</td>
<td>Mean 34.2 (29.1, 39.4)</td>
<td>32.1 (27.7, 36.5)</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>CV 0.59 (0.51, 0.67)</td>
<td>0.66 (0.59, 0.73)</td>
<td>0.28</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>Mean 0.79 (0.75, 0.82)</td>
<td>0.78 (0.75, 0.81)</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>CV 0.21 (0.19, 0.24)</td>
<td>0.18 (0.16, 0.20)</td>
<td>0.11</td>
</tr>
<tr>
<td>Orientation (degrees)</td>
<td>Mean 43.7 (40.9, 46.5)</td>
<td>43.7 (41.3, 46.0)</td>
<td>0.97</td>
</tr>
<tr>
<td></td>
<td>CV 0.60 (0.54, 0.65)</td>
<td>0.63 (0.59, 0.68)</td>
<td>0.33</td>
</tr>
<tr>
<td>Fractal dimension</td>
<td>1.38 (1.34, 1.41)</td>
<td>1.42 (1.39, 1.45)</td>
<td>0.15</td>
</tr>
</tbody>
</table>

4.4.2 Dynamic Analysis

Example plots of the time series corresponding to the y-axis position, grip force, and axial force are shown for one child with ASD and one typically developing child (see Figure 4.3). The correlation between grip and axial force is apparent in these plots.

Results for the comparison of kinetic variables are summarized in Table 4.3. Mean axial and grip forces were significantly lower in the ASD group (axial: $p = 0.05$; grip: $p = 0.04$). The coefficient of variation of the axial force was higher for the ASD group ($p = 0.002$), while maximum correlation was lower ($p = 0.003$). The maximum correlation time showed high variation within groups, and therefore no differences were apparent between groups. Ratio of maxima was also found to be similar between groups ($p = 0.41$).
Figure 4.3: Examples of a 5-second window showing the vertical position of the stylus on the tablet with corresponding summed grip force and axial force for (a) one child with ASD, and (b) one typically developing child.

### 4.5 Discussion

Spatial measures revealed very few differences between children with ASD and children who are typically developing in the spatial quality of their circle drawing traces. Differences between point estimates for each group were small and confidence intervals for these estimates overlapped significantly between groups (see Table 4.2), strongly indicating a

<table>
<thead>
<tr>
<th>Measures</th>
<th>ASD</th>
<th>TD</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial Force (N)</td>
<td>Mean 1.42 (0.92, 1.93)</td>
<td>2.19 (1.76, 2.61)</td>
<td>0.05*</td>
</tr>
<tr>
<td></td>
<td>CV 0.65 (0.53, 0.77)</td>
<td>0.34 (0.24, 0.44)</td>
<td>0.002*</td>
</tr>
<tr>
<td>Grip Force (N)</td>
<td>Mean 3.05 (1.67, 4.43)</td>
<td>5.28 (4.10, 6.45)</td>
<td>0.04*</td>
</tr>
<tr>
<td></td>
<td>CV 0.31 (0.21, 0.41)</td>
<td>0.32 (0.23, 0.40)</td>
<td>0.96</td>
</tr>
<tr>
<td>Max Correlation</td>
<td>0.84 (0.81, 0.87)</td>
<td>0.91 (0.89, 0.94)</td>
<td>0.003*</td>
</tr>
<tr>
<td>Delay (ms)</td>
<td>-77.8 (-261.7, 106.1)</td>
<td>-22.1 (-178.6, 134.4)</td>
<td>0.69</td>
</tr>
<tr>
<td>Ratio of maxima</td>
<td>1.34 (0.58, 2.09)</td>
<td>1.81 (1.17, 2.45)</td>
<td>0.41</td>
</tr>
</tbody>
</table>

Table 4.3: Statistics for kinetic movement variables and cross-correlation. The maximum cross-correlation was computed for the grip and pressure time series’. Ratio of maxima refers to the ratio of grip:axial peaks. Results for each group are reported as Mean (95% Confidence Interval: Lower, Upper). Results with p values below a significance level of 0.05 are indicated with *.
lack of difference between groups in the majority of the measures tested. Children with ASD showed marginally increased variability in the measure of area, which may have been due in part to concentration issues. Increased variability can also indicate impaired movement planning or error correction [22].

Despite slight differences in size, young children with ASD appear to be capable of producing shapes comparable in quality to typically developing peers in simple drawing tasks. This may seem to contradict previous handwriting studies, which have shown differences in letter formation in children with ASD [33, 34, 95]. However, handwriting is a complex task involving many motor, cognitive and visual-motor integration requirements that may not have been involved in a simple graphomotor activity such as circle drawing. Children have achieved a level of automaticity and proficiency in circle drawing, and it should require very little cognitive input and concentration at this point. Visual perception and visual-motor integration problems in ASD have been hypothesized to contribute to handwriting difficulties in this population [88], and given the relative task simplicity of circle drawing, we suspect that these skills may not have been used extensively in this task. The majority of children in this population have likely mastered circle drawing and therefore reliance on vision for distinguishing shapes during planning phases of movement or for error correction during execution has decreased [107, 108]. With decreased reliance on these skills that children with ASD appear to struggle with, our results indicate that they are able to compensate for fine motor differences to produce traces comparable to those by typically developing children.

While no major differences in quality were observed, differences were seen in many of the kinetic process variables. In particular, mean axial and grip forces were diminished in children with ASD (axial: $p = 0.05$, grip: $p = 0.04$). Literature reports of grip force in children with ASD have been inconsistent. While Hardan et al. [20] observed weak grip strength in children with ASD, David et al. [22] reported no difference in grip force in a grasp and place task. Another study suggested that children may use increased
proprioception in order to compensate for difficulties in visual perception and visual-motor integration [100], indicating that grip forces may be higher in order to increase proprioception. Studies have yet to examine dynamic characteristics of handwriting in children with ASD, but a recent study associated a decreased average grip force with fatigue and decreased legibility in a handwriting task in typically developing children [109]. Our results seem to agree with previous research indicating reduced grip strength in children with ASD, which may have a significant affect on fine motor activity.

Our results also showed an increase in the variability of the axial force measure \( p = 0.002 \). Early studies in handwriting pressure suggested that high variability in point pressure (axial force) was indicative of low legibility in handwriting [110, 111], while average axial force was not predictive. Graphomotor tasks require careful modulation of output to maintain fluency, with muscle stress and tension hampering the free flowing movement necessary to produce legible handwriting [21]. Combined, these results seem to indicate that when drawing or writing, grip force on the drawing implement should be carefully modulated and axial pressure should remain tightly coupled in order to produce legible handwriting. In children with ASD, it appears that grip force may be under-used for modulation (as evidenced by lower average grip force), such that additional variability in the axial force is necessary to maintain fluency of the pen trace. This could represent a maladaptive strategy to account for weaker grip strength or other fine motor difficulties. Weaker grip strength [20] and excessive rigidity [112] may translate to a decreased ability to make corrections while drawing, therefore over-corrections are manifested in axial rather than grip force. While this does not appear to affect the quality of the output in this analysis, it may be suggestive of movement inefficiencies and premature onset of fatigue in children with ASD [97].

Previous studies have shown a significant relationship between grip and normal forces [8, 99], but this relationship was found to be similar in children with and without motor difficulties. We also observed a significant correlation (as measured by the maximum
cross-correlation) between grip and axial forces. However, in the present study, this relationship was found to be reduced in children with ASD compared to typically developing children. This measure may be predictive of motor difficulties in this population, consistent with a previous study showing impairment in coordination of grip and load forces [22]. While the coordination of grip and axial forces seems to be impaired, children with and ASD are making similar numbers of adjustments in grip and axial forces (as seen in the ratio measure). This suggests that while grip adjustments are being successfully translated into axial adjustments in children with ASD, the amplitude is inappropriate for the task. Results indicate that modulation of grip and axial forces is different in children with ASD, and future studies should examine the implications of these differences in terms of energy expenditure and muscle fatigue.

Taken together, the results relating to spatial and kinetic characteristics of a circle drawing task may indicate that the cognitive demands of the task play a role in graphomotor difficulties in children with ASD. Differences in the accuracy of letter formation have often been observed in children with ASD [33, 94, 95], but when a simple drawing task is used, our data suggest that spatial quality is preserved. Despite task simplicity however, kinetic process measures significantly departed from values observed in typically developing children (both in terms of modulation and coordination of forces). It is therefore important for future studies of graphomotor abilities in this population to investigate process variables, in addition to outcome variables. This will contribute to a fuller picture of fine motor impairments in children with ASD. Understanding the specific nature of motor deficits will aid in targeted treatment for these impairments. This analysis should be extended to handwriting in older children with ASD to facilitate interventions which could improve graphomotor skills, which are so important for academic performance, communication, and self-esteem [29].

This study had two limitations. Firstly, the small sample size may not have allowed sufficient power for detection of differences in the spatial measures. However, differences
in point estimates were generally small and confidence limits overlapped significantly for these estimates, strongly indicating no difference between groups. Secondly, although all participants with ASD had FSIQ > 70 (high functioning ASD), differences in cognitive strengths and weaknesses, as well as age and gender differences between groups may have influenced the results. NVIQ was therefore included in the regression model so that drawing characteristics were compared after correcting for age, gender, and NVIQ. Future research might include a comparison group with a known intellectual disability to better determine the effect of cognitive levels on handwriting and drawing.

4.6 Conclusions

This study offers additional evidence of fine motor difficulties in children with ASD, particularly as related to kinetic process variables such as grip and axial forces, as well as the relationship between the two. Children with ASD show increased variability in axial force, and decreased mean axial and grip forces, suggesting differences in kinetic modulation to maintain quality and fluency in the pen trace. Understanding the specific nature of motor deficits is the first step towards developing targeted treatment for these impairments. Future studies should incorporate kinetic process measures and extend these results to handwriting analysis to facilitate interventions which could improve graphomotor skills, which are so important for academic performance, communication, and self-esteem.
Chapter 5

Conclusions

5.1 Contributions

The main contributions of this thesis are summarized below.

1. *Quantification of statistical persistence in circle drawing in a pediatric population.*
   Previous works have shown statistical persistence in circle drawing and handwriting samples in an adult population [66], and in gait dynamics in adults and children [18, 78]. However, this is the first known quantification of statistical persistence for upper limb dynamics in typically developing children. Fractal dynamics have been known to mature with age, and have successfully distinguished between populations with various motor difficulties [17, 69]. A description of relevant neurotypical fractal dynamics is an important first step in being able to accurately describe altered fractal dynamics of fine motor activity.

2. *Identification of practical limitations of fractal dynamics.* Although fractal dynamics of gait have been shown to distinguish between individuals with and without various motor difficulties, the study of fractal dynamics of fine motor activity has yet to yield similar results. This research indicates that perhaps this measure is not adequately sensitive to detect subtle differences in upper limb dynamics, and
other measures, such as the Lyapunov exponent [70, 113] should be considered in future work.

3. *Extension of results elucidating timing differences between typically developing children and those with ASD.* Previous research has identified differences in discontinuous timing in children with ASD as compared to typically developing controls [85], likely related to cerebellar differences in this population. Previous studies have used a continuation paradigm, which is difficult for young children as they have trouble synchronizing with a metronome. The current study outlines timing differences in a self-paced drawing task with no explicit instructions given to ensure consistent timing, and confirms that timing differences are visible in children as young as 4 years of age. Timing affects a variety of gross and fine motor functions, and quantification of difficulties may have implications for early intervention and therapy.

4. *Determination of kinetic difficulties in a graphomotor task in children with ASD.* Studies of graphomotor abilities in children with ASD have previously focussed on static outcome variables [88], while kinetic process variables have distinguished between individuals with different movement disorders [8, 96, 97]. Our results confirm that difficulties in the coordination of grip and normal forces are present in children with ASD. Understanding motor difficulties can aid in targeted interventions and kinetic measures should therefore be included in future handwriting research.

5. *Determination of a relationship between kinetic variables and spatial quality of circle drawing in children with ASD.* Although differences were observed in kinetic variables, spatial quality of circle drawing was found to be very similar between children with ASD and their typically developing peers. This suggests that perhaps children with ASD have developed a maladaptive strategy to account for decreased grip strength and other fine motor difficulties, allowing them to produce acceptable
quality output in a simple drawing task. Handwriting studies have shown that more complex graphomotor tasks reduce the quality of output in this population, suggesting that this strategy is not ideal.

Overall, this work has increased the body of knowledge relating to graphomotor abilities in children with ASD. Understanding the specific nature of motor deficits is the first step towards developing targeted treatment for these impairments. Now that we understand that kinetic variables may be an important factor in the graphomotor difficulties often observed in children with ASD, devices which measure grip and axial forces during writing or drawing tasks could be used in a clinical setting to develop targeted intervention related to specific difficulties on a child by child basis. More information about the relationship between observed differences in kinetic variables and poor handwriting in children with ASD is necessary before this research can be clinically applicable.

5.2 Future Work

Future studies should incorporate kinetic process measures and attempt to extend our results elucidating differences in these variables to handwriting analysis in children with ASD. This is the logical next step in beginning to facilitate interventions which could improve graphomotor skills, which are so important for academic performance, communication, and self-esteem.

With the current data set, many different types of analysis are possible, but given time constraints, we were only able to complete those outlined above. Future work might look more closely at grip force differences between groups, as differences were in fact observed in the modulation of grip and axial forces between groups. For example, previous studies have characterized the fractal dynamics of grip force [66]. This might therefore be an interesting measure, since although no differences were observed in the fractal dynamics of drawing time, the graphomotor difficulties experienced by children with ASD may be
constrained to kinetic variables in this simple task. For the purposes of this analysis, the grip force was summed over all sensors to give a grip force time series, however, previous drawing studies have also looked at the distribution of grip force (grip pattern), and how this relates to handwriting proficiency [8]. This type of analysis could also be done on current or future grip data in children with ASD.
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