

Pencil Grasp Pattern: How Critical is it to Functional Handwriting?

by

Heidi D. Schwellnus

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Graduate Department of Rehabilitation Science
University of Toronto

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Abstract

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This thesis reports the results of a large study to evaluate the kinetics of pencil grasp patterns in terms of speed and legibility of handwriting of children in Grade 4. Current clinical practice as recent as 2008 suggests that teachers identify the dynamic tripod pencil grasp as an optimal pencil grasp for handwriting. Research findings had suggested that three other pencil grasps may be functional for handwriting, though there was still inconclusive evidence upon which to base clinical practice. The purpose of the present study was to: assess the impact of pencil grasp on the speed and legibility of handwriting; to determine the effect of grasp on speed and legibility following a 10-minute copy task intended to induce fatigue; and to describe the axial and grip forces of the four pencil grasps. 120 children were assessed, completing a standardized handwriting assessment before and after a 10-minute copy task. The participants utilized an instrumented pen and wrote on a digitizing tablet, which measured, respectively, the axial and grip forces associated with their grasp patterns. Pencil grasp was not found to impact the speed or legibility of the written product in either short or long duration copy tasks. Fatigue decreased the legibility of the product across all pencil grasps but increased the speed across all pencil grasps equally. Grip and axial forces were only different in grasps with an adducted thumb and mainly during the initial assessment. Collectively, these results suggest that four mature grasps are equally functional for handwriting in children of this age. These findings contradict common clinical impressions that the dynamic tripod pencil grasp is optimal.

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Education is not a preparation for life; education is life itself. John Dewey (1859-1952)

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Chapter 1

Background and Rationale

1. Background

1.1. Introduction

Evidence based interventions are key in any field and needed in occupational therapy (Law & Baum, 2000). Handwriting is an area of occupational performance that is still important for school-aged children to master (Longcamp et al., 2008). Handwriting requires a combination of lower (motor planning) and higher (executive) level cognitive skills (Graham & Weintraub, 1996). Only when the lower level skills become automatic are children able to simultaneously use both lower and higher skills similar to adults (Graham & Weintraub). There is new compelling support for the continued focus on learning to handwrite letters from a study by Longcamp and colleagues (2008). In their study, the memory for the handwritten designs facilitated the visual recognition of the same design, reducing the potential of confusion with mirror images. This finding supports the continued importance of learning to handwrite as it appears to create a motor program of the direction and number of strokes making up the letter (Longcamp et al., 2008).

Children spend up to half of their school day writing (McHale & Cermak, 1992) and need to write for longer and longer periods of time as they progress higher in grades. When a teacher determines that a student is having problems with the production of legible writing (Feder, Majnemer, Bourbonnais, Blayney & Morin, 2007), an occupational therapist is often consulted (Graham et al., 2008). In fact, handwriting difficulties are the most common reasons for referral to occupational therapists in school-aged children (Feder, Majnemer, & Synnes, 2000; Jongmans, Linthorst-Bakker, Westenberg, & Smits-Engelsman, 2003; Ratzon, Efraim, & Bart, 2007; Selin, 2003). With approximately 30% of occupational therapists working in paediatrics, and 50% of these working with school-aged children (Asher, 2006), considerable financial and human resources are invested in school-based therapy. This necessitates that evidence-based interventions be used. When a child has handwriting difficulties without a diagnosis of a neurological or intellectual disability, the handwriting difficulties are often termed dysgraphia (Feder, & Majnemer, 2007, Maeland, 1992).

The reported prevalence of handwriting difficulties in school-aged children in the literature ranges from between 10 % to 34 % (Smits-Engelsman, Niemeijer, & van Galen, 2001), although a 2010 study suggested that some of these difficulties are transient and the actual percentage of persistent handwriting difficulties is closer to 6% in Grade 3 (Overvelde & Hulstijn, 2011). Their research suggested that a high percentage of handwriting difficulties are transient, with only 6% being persistent. Handwriting difficulties can profoundly affect children's development. Handwriting difficulties negatively impact children's academic performance and, in turn, may also affect perceptions of a child's abilities, self-esteem, and personal relationships (Graham & Weintraub, 1996). For this reason, they must be addressed with evidence-based interventions.

Typically, the dynamic tripod grasp is recommended as the correct grip for handwriting (Benbow, Hanft, Marsh, & Royeen, 1992; Callewaert & Herrick, 1963; Graham et al., 2008) despite a lack of empirical evidence to support either the necessity of a dynamic tripod grasp or its advantage in terms of improved functionality of written output (Dennis & Swinth, 2001; Koziatsek & Powell, 2003; Schneck & Henderson, 1990). When working with children with handwriting difficulties, occupational therapists will frequently assess the child's pencil grasp and then intervene by altering the pencil grasp (Rigby & Schwellnus, 1999, Feder et al., 2007). However, without evidence that pencil grasp impacts the longevity and functionality of writing (both speed and legibility), this clinical practice is questionable and may be an inefficient use of resource funding in school-based therapy. This study took advantage of technological developments to investigate children's pencil grasp pattern kinetics and the impact of grasp pattern and fatigue on the speed and legibility of written output.

1.2. Pencil Grasp

Pencil grasp is a term used to describe the position of the fingers involved in grasping a pencil. There are two distinct types of grips, which were described by Napier (1956) as a power grasp or a precision grasp. A power grasp clamps the object between the fingers and the palm with the thumb in the same plane as the fingers. A precision grasp pinches the object between the fingers and the thumb with the thumb in opposition to the fingers. The most commonly used pencil grasp is termed the (dynamic) tripod grasp (Wynn-Parry, 1966), which involves the thumb, index and middle fingers functioning as a tripod. This grasp allows small, well coordinated

movements of the involved fingers. A 2008 survey of teachers found that four out of five teachers taught students to use a dynamic tripod grasp when holding a pencil (Graham et al., 2008).

Although the dynamic tripod grasp is encouraged by both occupational therapists and educators, a number of alternate grasp patterns exist. Benbow (1987) found that less than half of the Grade 2 children (aged 6 years 8 months to 7 years 8 months) involved in her study had achieved the dynamic tripod grasp, results which contradicted earlier research. Instead, the children used another grasp pattern, termed the (dynamic) quadropod grasp. This grasp was very similar to the tripod grasp but involved the thumb and three fingers. Schneck and Henderson (1990) identified an additional dynamic grasp pattern, the lateral tripod grasp, which was found to be the second most common grasp pattern in children over 5 years of age. Dennis and Swinth (2001) identified a fourth grasp pattern, the lateral quadropod grasp, which they stated was also acceptable for use when writing (See Figure 1). In fact, Koziatek and Powell (2003) found the distribution of these grasp patterns was relatively equal with 38% of Grade 4 students using the dynamic tripod grasp, 21% using the lateral quadropod, 22% using the lateral tripod and 18% using the dynamic quadropod grasps. The question remains: are these grasps as functional as the dynamic tripod grasp for longer term writing?

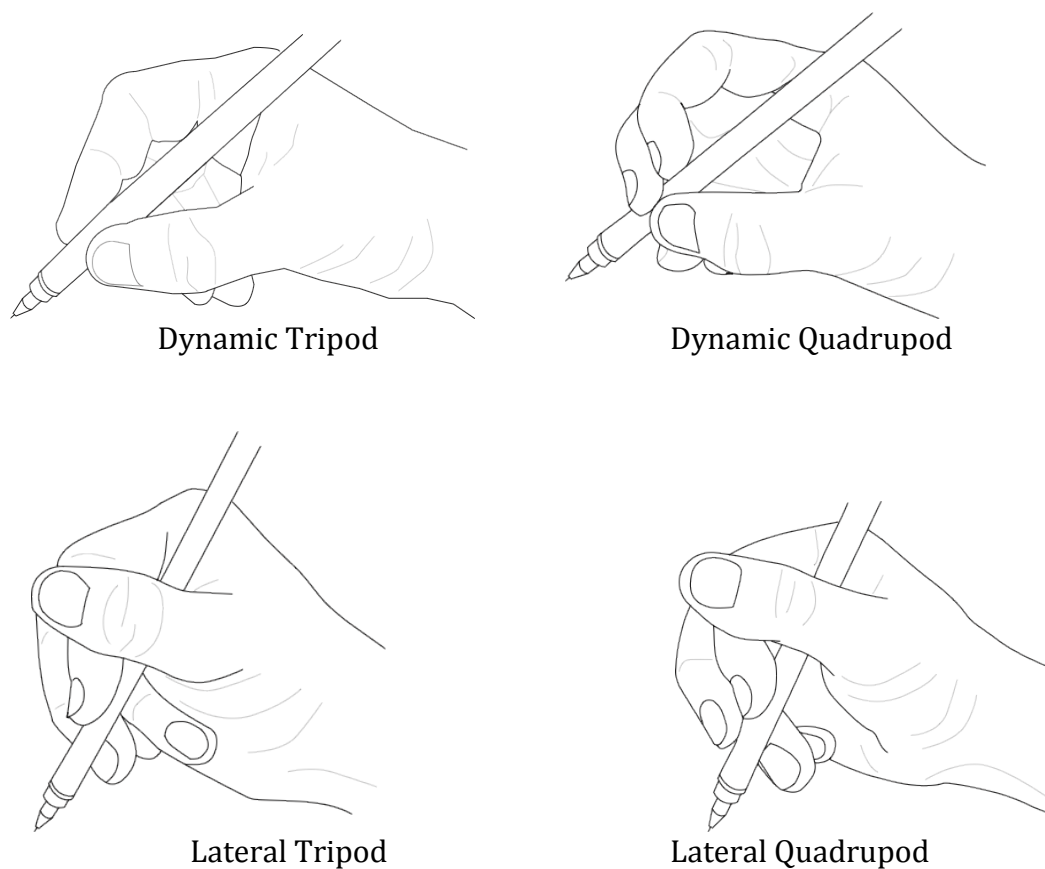


Figure 1-1: Four Mature Grasp Patterns

1.2.1. Biomechanical nature of pencil grasps

The tripod grasp involves the thumb, index and middle finger in opposition, functioning as a “tripod” and allowing small, very co-ordinated movements. The fourth and fifth fingers are flexed into the palm at the metacarpo-phalangeal (MCP) joint, providing stability. In the dynamic tripod grasp, the movements of the pencil originate from the interphalangeal (IP) joints of the hand and the intrinsic muscles of the hand, compared to the static tripod grip where the movement of the pencil originates from the extrinsic muscles of the shoulder, elbow and wrist (Elliott & Connolly, 1984). In other words, when a person holds a pencil to write, this involves manipulation of the pencil through flexion and extension of the digits within the hand via the intrinsic muscles of the hand, while the extrinsic muscles provide stability for the movement. Therefore, it has the biomechanical abilities for fine manipulation (Elliott & Connolly). It is for these reasons that the dynamic tripod grasp is suggested to have an advantage over other pencil

grasps including the dynamic quadrupod, the lateral tripod and the lateral quadrupod pencil grasps (Schneck, 1991).

The biomechanics of the dynamic quadrupod pencil grasp are very similar to that of the dynamic tripod, with the difference being the inclusion of the ring finger on the shaft of the pencil. This alters the mechanics of the pencil grasp because the radial/ulnar dissociation is lost as the ring and, through coupling, the little finger, are no longer used for stabilization in the palm of the hand but are incorporated into the grasp responsible for the movement of the pencil (Benbow, Henderson, & Pehoski, 1995).

The biomechanics of the lateral grasps are also similar to that of the dynamic tripod grasp. In particular, the lateral grasps still allow for the movement of the pencil to originate from the interphalangeal joints of the hand (Bergmann, 1990), though they differ from the dynamic grasps in terms of thumb position. The thumb is in a position of opposition in the dynamic grasps, but with the lateral grasps, it is in one of adduction. As such, the pencil movement comes from the index, middle and ring fingers (if a quadrupod grasp). The thumb's adducted position closes the webspace and makes contact with the pencil at the interphalangeal carpal bone, not the thumb pad.

Though the biomechanical positioning is different across the four grasps, there has been no literature to indicate that the grasps produce less legible or slower writing; in fact, the opposite has been found with children using the dynamic quadrupod pencil grasp scoring the highest on speed and legibility (Koziatsek & Powell, 2003).

1.2.2. Development of pencil grasps

Children initially use immature grasps when they first hold pencils or crayons (Benbow, 1987), and then these transition into mature grasp patterns, which include, but are not limited to, the tripod grasp. The tripod grasp typically develops in children between the ages of 4 to 6 (Rosenbloom & Horton, 1971; Schneck & Henderson, 1990) and continues to be refined up to age 14 (Ziviani, 1983). The tripod has two stages, a static stage which transitions into a dynamic stage around the age of 4-6 years (Rosenbloom & Horton, 1971). There is a paucity of literature

on the development of the other three grasp patterns; however, although speculation is that they result from an increased need for stabilization of the pencil in the hand (Benbow, 1987).

1.2.3. Motor control of forces involved in pencil grasps

The dynamic tripod grasp is suggested to balance the forces involved in holding the pencil so as to limit the required amount of force used to manipulate the pencil to make letters (Soechting & Flanders, 2008). The other grasp patterns all have more surface area contact with the pencil and this may impact the control of the pencil and the forces involved in that manipulation. With more surface area, there may be a decrease in the force exerted by each digit because the total force is distributed over a larger surface area. Alternatively, with more digits involved, the amount of force may increase. Both changes may cause greater fatigue, as more effort is required to move the pencil (Dennis & Swinith, 2001; Tseng & Cermak, 1993). Indeed, the lateral tripod grasp has previously been linked to earlier development of fatigue (Stevens, 2008). A study by Engel-Yeger and Rosenblum (2010) found that the tripod pinch strength of students with dysgraphia was lower and that their strength decreased significantly after a motor control task and a copy task compared to students without dysgraphia.

1.3. Pencil Grip and Writing Speed and Legibility.

The impact of pencil grasp on handwriting has been a topic of investigation since the 1940's when Wiles (1943) suggested that the primary sized pencils had no impact on the young children's grasp pattern or written output. Sassoon, Nimmo-Smith and Wing (1986), Ziviani and Elkins (1986) and Tseng and Cermak (1993), studied pencil grasp and speed and legibility of written output. The results suggested that alternate grasp patterns did not appear to be linked to poor written output, a finding that has since been corroborated (Dennis & Swinith, 2001; Koziatek & Powell, 2003; Selin, 2003). A standing criticism of the research was that the grasp patterns were categorized from either a photograph or videotape evidence and, as such, the authors were unable to investigate or quantify the dynamic nature of the kinetics and kinematics of the grasp patterns. Current technology allows for the analysis of pressure distribution from the fingers in contact with the pencil shaft, as well as on the writing surface to determine the dynamic nature of the four grasp patterns.

1.3.1. Previous research on pencil grasp and handwriting

There has been considerable research into pencil grasp and handwriting. There have been contradictory findings regarding whether children who use non-dynamic tripod pencil grasps have decreased legibility or speed of writing (Koziatek & Powell, 2003; Schneck, 1991; Ziviani, 1982). What is lacking is a study that identifies the pencil grasps of children by video analysis, uses a standardized writing assessment before and after a longer copy task to induce fatigue and one that measures the axial and grip forces involved in the pencil grasps.

1.3.2. Pencil grasp and standardized writing assessments

The dynamic tripod grasp has been promoted as the optimal pencil grasp for writing (Bonney, 1992; Tseng & Cermak, 1993), however, other literature has not supported the notion that the dynamic tripod grasp is necessary for functional writing. A further criticism is that often the studies have not used a standardized handwriting assessment to determine legibility (Dennis & Swinth, 2001; Koziatek & Powell, 2003; Rosenblum, Dvorkin, & Weiss, 2006; Sassoon et al., 1986; Ziviani & Elkins, 1986). Dennis and Swinth (2001) used regular classroom assignments to evaluate legibility, Ziviani (1986) used standardized phrases but did not use a standardized method of evaluating legibility, Sassoon (1986) used three common sentences but did not evaluate legibility. A study by Koziatek (2003) did use a standardized handwriting assessment with the four pencil grasps and found no difference in speed or legibility between the four grasp patterns; however, they did not use a lengthy task was used nor were the forces involved measured.

1.3.3. Pencil grasp and fatigue

As children progress through school, the length of the typical class assignment becomes longer (Cornhill & Case-Smith, 1996, Tseng & Chau, 2000). Fatigue involved in longer writing tasks has been recognized as a factor that affects the amount and quality of written output of children (Dennis & Swinth, 2001; Tseng & Cermak, 1993). However, most research conducted with children with and without handwriting difficulties has utilized a standard handwriting assessment, which requires short samples of writing (Tseng & Cermak, 1993). Parush, Pindak, Markowits and Karsenty (1998) conducted a study of Grade 3 students which involved a

pre/post standardized assessment with a 10-minute copy task embedded in between. They assumed fatigue would be generated by the copy task but did not measure fatigue. In addition, they did not classify grasp pattern. Graham and Weintraub (1996) conducted a review of literature and concluded that the impact of fatigue while using the alternate grip patterns during longer writing tasks had not been investigated.

1.3.4. Pencil grasp and kinetic variables (Axial and Grip)

Grip and axial force have been implicated in writing for a number of years, including research dating back to the 1950's (Harris & Rarick, 1957; Harris & Rarick, 1959). Axial force, previously termed point pressure, was noted to be more variable for students with higher legibility scores when the students increased their writing speeds (Harris & Rarick, 1957; Harris & Rarick, 1959). Parush et al., (1998) found similar results, reinforcing the suggestion that children with poor handwriting have less consistency in axial pressure. The pressure in this last study was measured by carbon copy, not mechanically. Chau et al., (2006) using an instrumented pen, found that grip forces were able to distinguish between children with and without disabilities who were able to copy a single sentence and suggested further study with larger populations.

1.4. New technology to augment clinical assessment

With technological advancements, new instruments have been developed that allow the measurement of kinetics and kinematics of writing. Specifically, digitizing tablets measure the axial or downward force exerted during writing (Rosenblum, Parush, & Weiss, 2003), while instrumented styli with pressure sensors around their circumference measures the forces exerted by the fingers on the barrel or shaft of the pencil during writing (Baur, Furholzer, marquardt & Hermsdorfer, 2009; Chau et al., 2006; Hooke, Park & Shim, 2008; Kutz, Wolfel, Meindl, Timmann & Kolb, 2009}. Both these technologies assist in further investigating the potential functioning of pencil grasps for writing in school-aged children.

1.5. Rationale, thesis objectives and study overview

In light of the findings from the literature, there is still a gap between research results concerning pencil grasp functionality and the clinical practice of recommending the dynamic tripod pencil

grasp. Even with research evidence to the contrary, pencil grasp is still an area that is documented by teachers as a problem (Graham, et al., 2008) and also a key area targeted by occupational therapists for remediation (Feder & Majnemer, 2007; Benson, Salls, & Perry, 2010). Biomechanical differences between the common grasp patterns have been illustrated, but what is lacking is knowledge about whether these differences impact the functionality of handwriting. To assist in bridging this gap, the overall objective of the thesis was to investigate the functionality of four pencil grasps on written output. To accomplish this, the objectives of this study were to determine: 1) the impact of pencil grasps on the speed and legibility of written output of children in Grade 4; 2) the impact of a prolonged writing task on the speed and legibility of written output of with different pencil grasp patterns; and 3) the relationship of grip and axial forces of four common pencil grasp patterns at the beginning of a writing task and after a fatigue-inducing task.

A study was undertaken to evaluate the speed and legibility of handwriting produced by Grade 4 children before and after a prolonged (10-minute) copy task. The children wrote on a self-inking tablet with an instrumented pen to allow for both axial and grip forces to be measured. The children completed a self-report perceived efficacy scale at four times during the study to obtain an indication of the effort that they expended during the prolonged copy task. A standardized handwriting assessment, the Children's Handwriting Evaluation Scale, (CHES: Phelps & Stempel, 1987), was administered to the children before and after the copy task to allow for evaluation of speed and legibility of writing at both times. The children were also asked questions on their opinion of their own writing through a scale, the Children's Questionnaire for Handwriting Proficiency, the CHaP (Engel-Yeger, Nagauker-Yanuv & Rosenblum, 2010). The CHaP is the companion scale of the Handwriting Proficiency Screening Questionnaire (HPSQ: Rosenblum), which was completed by the participating teachers.

In this project, the results of the study were divided into three manuscripts, each one addressing one of the three objectives of the study. To answer the question regarding how pencil grasp impacts upon the speed and legibility of handwriting, (Chapter 2) the results from the CHES assessment for all 120 children who participated in the study were analyzed. Chapter 3 addressed the findings regarding the impact of the prolonged copy task on each of the pencil grasps and utilized the data from all 120 students. Grip and axial forces were the subject of

Chapter 4. This chapter involved 74 students who used only the four key pencil grasp patterns and it reported the results of the impact of the prolonged copy task on the grip and axial forces of each of the pencil grasp patterns. Chapter 5 provided a discussion of the findings, and presents recommendations for clinical practice and further research.

The primary author wrote the study proposal, obtained ethical clearance, conducted the study and analyzed the data. Manuscripts written from the data included in this thesis were written by the primary author. Dr. C. Chau and Dr. H. Carnahan primarily provided methodological and editorial guidance, as did Dr. H. Polatajko and Dr. C. Missiuna as committee members. All members of the committee requested that their names be included in the manuscripts.

Chapter 2

The Effect of Pencil Grasp on the Speed and Legibility of Handwriting in Children

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2. The Effect of Pencil Grasp on the Speed and Legibility of Handwriting in Children

2.1. Abstract

Introduction: There is evidence that pencil grasps other than the dynamic tripod may be functional for handwriting. This study examined the impact of grasp on handwriting speed and legibility.

Methods: A sample of 120 typically developing fourth grade students were videotaped while performing a writing task. The grasps used were categorized and the writing evaluated for speed and legibility using a handwriting assessment. Linear regression analysis examined the relationship between grasp and handwriting.

Results: Six categories of pencil grasp were documented: four mature grasp patterns, one immature grasp and one alternating grasp. Multiple linear regression results revealed no significant effect for grasp for either legibility or speed.

Conclusions and significance of the study: Pencil grasp patterns did not influence handwriting speed or legibility in typically developing children. This finding adds to the mounting body of evidence that alternative grasps may be acceptable for fast and legible handwriting.

2.2. Introduction

Handwriting is an essential life skill required of children in school; however, 10-34% of school-aged children fail to master handwriting (Smits-Engelsman, Niemeijer & van Galen, 2001). In particular, proficient handwriting is necessary for completion of academic activities such as note taking, assignments and exams (Amundson & Case-Smith, 2004). Handwriting difficulties can profoundly affect children's development, negatively impact their academic performance and, in turn, may be detrimental to self-esteem, personal relationships and perceptions of a child's abilities (Graham & Weintraub, 1996).

Teachers are typically responsible for providing handwriting instruction. When a teacher determines that a student is having problems producing legible writing, an occupational therapist (OT) is often consulted (Feder, et al., 2007). In fact, handwriting difficulties are the most common reasons for referrals to OT in school-aged children (Graham et al., 2008). Handwriting difficulty without neurological or intellectual disabilities is often termed dysgraphia, and typically includes poor legibility and reduced speed of writing (Feder et al., 2007; Maeland, 1992).

2.2.1. Grasp Patterns

In a 2008 survey, 41% of 169 teachers identified “incorrect” pencil grasp as a common handwriting difficulty (Graham, et al., 2008). OTs addressing handwriting difficulties often suggest, as a solution, adoption of the dynamic tripod grasp (Rigby & Schwellnus, 1999). Various grasp taxonomies have been proposed (Dennis & Swinth, 2001; Schneck & Henderson, 1990; Selin, 2003, Tseng, 1998). Generally, a grasp is labeled according to the nature of the finger or palm contact with the pencil and the movement of the pencil. Over the course of child development, a number of grasp patterns emerge. Young children initially use primitive grasps (Tseng, 1998), where the fingers are not in opposition to one another and the whole forearm produces pencil movement (Saida & Miyashita, 1979). Transitional grasps emerge next, include the cross thumb, the four-fingered and the static tripod grasps, where the wrist, serves as the main source of pencil movement (Tseng, 1998). These first two categories of grasp patterns are often referred to as immature or static grasps. Eventually, mature grasp patterns develop (Dennis & Swinth, 2001; Koziatsek & Powell, 2003). In this last category, the flexion, extension and lateral movement of either three or four fingers control pencil movement (Long, Conrad, Hall, & Furler, 1970). Four grasp patterns (Figure 1) have been identified as mature and appropriate for functional writing. Each grasp is detailed below.

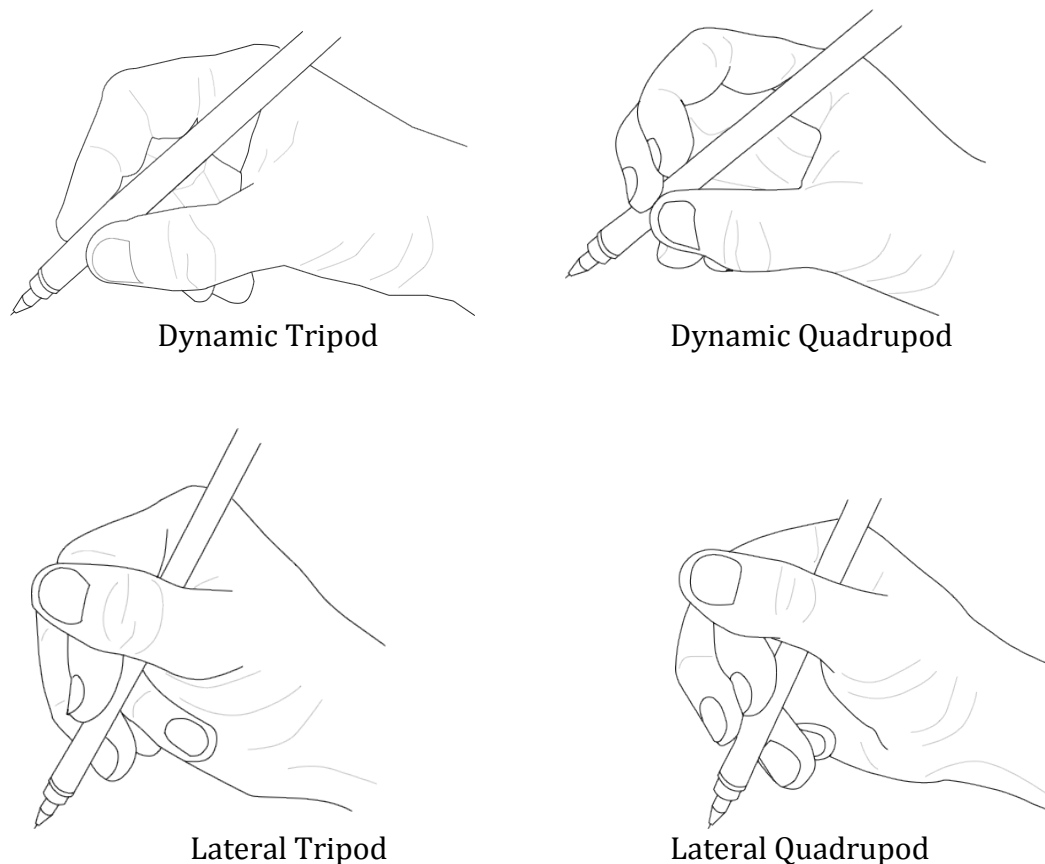


Figure 2-1: Four Mature Grasp Patterns

1. **Dynamic tripod (DT)**: The most commonly recommended pencil grasp for handwriting (Schneck & Henderson, 1990). This grasp involves the thumb, index and middle fingers, functioning as a tripod (Benbow, Hanft, Marsh & Royeen, 1992). The dynamic tripod grasp allows for small well-coordinated movements of the fingers originating from the interphalangeal (IP) joints and muscles of the hand and forearm, (Elliott & Connolly, 1984; Trombly & Cole, 1979). This grasp develops between the ages of 4 to 6 (Schneck & Henderson, 1990) and continues to be refined up to the age of 14 (Ziviani, 1983).
2. **Lateral (thumb) tripod (LT)**: This is the second most common grasp pattern described in the literature (Schneck & Henderson, 1990). In this grasp, the thumb is adducted against the lateral aspect of the index finger and often crosses over the top of the writing utensil. By nature of its position, the thumb is not involved with the distal movement of the pen but the index and middle fingers initiate pencil movement.

3. Dynamic quadrupod (DQ): This grasp is very similar to the dynamic tripod grasp but involves the thumb and three fingers. Benbow (1987) found it a common grasp pattern of Grade 2 children. The same distal manipulation of the pencil occurs with this grasp.
4. Lateral (thumb) quadrupod (LQ): This grasp, identified by Dennis and Swinth (2001), is similar to the lateral tripod, except that four fingers contact the writing implement, with the index, middle and ring fingers initiating the pencil movement.

With all the above mature pencil grasp patterns, movement of the pencil is produced by the intrinsic muscles of the hand. In contrast, immature grasps invoke the extrinsic muscles of the arm leaving the fingers in a static posture (Elliott & Connolly, 1984). Thus the nomenclature of the lateral grasps described above should technically be prefaced with the word “dynamic”.

2.2.2. Grasp and functional writing

A 2008 survey of teachers found that four out of five teachers taught students the correct way to hold a pencil was the dynamic tripod (Graham et al., 2008). However, Koziatek and Powell (2003) found that the grasps of Grade 4 students were well-distributed among the four mature grasp patterns. While numerous studies have described pencil grasp development, only a handful has specifically investigated the impact of pencil grasp on handwriting quality, particularly, the speed of writing and the legibility of the written product. The findings reported in this handful of studies do not support the belief that the dynamic tripod grasp is essential for functional writing (Dennis & Swinth, 2001; Koziatek & Powell, 2003; Sassoon et al., 1986; Ziviani & Elkins, 1986). For example, Sassoon, Nimmo-Smith and Wing (1986), and Ziviani and Elkins (1986) described grasps as either DT or modified tripod, and reported that the latter was not linked to poor speed and legibility of written output. This finding was corroborated by Dennis and Swinth (2001) who classified grasps as either DT or “atypical” where atypical referred to all other grasps observed. Finally, when considering all the different grasp patterns, Koziatek and Powell (2003) also found that quality handwriting was not exclusive to the dynamic tripod grasp.

All the above studies categorized grasp patterns based on a single or a series of static photographs, and as such, the investigators were unable to capture or investigate the dynamic nature of the grasp patterns. A study with adults found that approximately a quarter of university

students reported that they used more than one grasp during writing (Stevens, 2008). Similarly, the use of multiple grasp patterns has also been noted in children (Parush, Pindak, Hanh-Markowitz & Mazor-Karsenty, 1998). Therefore, it may be advisable to videotape writing sessions to capture and retrospectively identify any changes in grasp patterns that occur. Only one of the above studies used a standardized handwriting assessment to judge the speed and legibility of the student's work, precluding straightforward comparison among studies. Given that there is no consensus in literature about the impact of pencil grasp on handwriting proficiency (Rosenblum, Dvorkin & Weiss, 2006), it is essential to confirm whether or not the dynamic tripod grasp is indeed associated with better quality and speed of writing. To address this question, we investigated the effect of grasp pattern on handwriting quality, using video records for grasp identification and a standard handwriting assessment for measuring speed and legibility.

2.3. Methods

2.3.1. Participants

A volunteer sample of 120 fourth grade students was recruited from 4 schools within a metropolitan school board. Students with physical disabilities were excluded from the study, however, those with developmental disorders such as learning disabilities or developmental coordination disorder were not excluded in order to have a proportion of non-proficient writers. All schools were situated in middle to upper middle class neighbourhoods according to Statistics Canada household income for the catchment area of each school. Ethical approval was received from both the school board and the associated university research ethics board. Written parental consent was received and each child assented to the study. Fourth grade students were selected because handwriting is generally considered to be well-developed by this age (Berninger, Fuller & Whitaker, 1996). Data collection took place in the spring for the majority of the students; however, to achieve the desired sample size, the study was extended and a small group, from a new cohort of Grade 4 students, was assessed in the fall of the next school year.

2.3.2. Instruments

The writing task was performed on an electronically inking and digitizing tablet (Wacom Cintiq 12WX). The sessions were video recorded in digital form (Sony Handicam, DCR-SR45). The children utilized an instrumented pen to write on the tablet. The barrel of the pen was 0.43 inches (11mm) in diameter, which is comparable to a primary school pencil. The pen tip provided high friction on the tablet surface to simulate writing on paper. The instrumented pen was used as part of a larger study investigating grip forces while writing.

To evaluate handwriting quality, the Children's Handwriting Evaluation Scale (Phelps & Stempel, 1987) was used. There is a manuscript (CHES-M) version for children in Grades 1 and 2 and a cursive (CHES) variant for children beyond Grade 2. The CHES-M consists of two sentences of printing whereas the CHES is longer, with five sentences. Both versions evaluate handwriting speed and legibility, and exhibit excellent psychometric properties (intra-reliability of 0.82 and inter-reliability of 0.95) (Phelps & Stempel, 1987). The CHES with Grade four students and can be administered in two minutes. The quality of writing is determined by a speed score (letters per minute) and scores on quality criteria. A student can be identified as needing remediation based on the rate and quality scores individually or in combination.

Although cursive is the expected style of writing in fourth grade in North American schools (Graham, Weintraub, & Berninger, 1998; Ontario Ministry of Education) the students all requested to write in manuscript. The students all had some exposure to cursive, but reported feeling more comfortable with manuscript. As a result, the legibility criteria for cursive writing were not applicable. To judge the legibility of the samples, the CHES-M legibility criteria were applied. Ten criteria are scored for each sample and a raw score out of 100 is calculated. A quality score of 80-100 indicates good legibility, a score of 50-70 indicates satisfactory legibility and a score of 40 and below indicates poor legibility. As the age of our sample was older than that prescribed by the CHES-M and the amount of writing was doubled, we did not use the above CHES-M cut-off. Rather, the quality scores were plotted and the 15% percentile was located, yielding a corresponding cut-off score of 30 (Graham et al., 2006). This cut-off was lower than the CHES-M threshold because there was twice the opportunity to make errors given the greater volume of text and the expected developmental increase in writing speed. The number of letters

written in each sample was counted and divided by two to get a value of letters per minute (LPM). As the age of the sample was higher than that for the CHES-M, only raw scores were considered.

The teachers completed the Handwriting Proficiency Screening Questionnaire (HPSQ) developed by Rosenblum (2008) as a confirmation of the presence of handwriting difficulties. The HPSQ is a 10-item multiple-choice questionnaire for teachers designed to identify students with handwriting difficulties among school-aged children. This questionnaire has good reliability and validity (0.84 for test-retest and 0.92 for inter-rater reliability). A score of 14 or greater is indicative of dysgraphia.

2.3.3. Procedure

Participants were assessed in a quiet room in their own school during regular school hours. The primary author, who is an experienced OT, completed all assessments. All children completed the CHES. Children sat comfortably on a height adjustable chair pulled up to a standard school table. Children's feet were supported on the floor and trunk movements were permitted as needed by the participant (Parush et al., 1998). Each child first practiced writing his or her name and a sentence or two of creative writing on the tablet for one-minute. Children then completed the CHES writing task. During the assessment, the primary author classified the children's grasp patterns as either one of the four mature grasp patterns described above or as an immature grasp pattern, termed "Other". The primary author also recorded whether or not the children switched grasp patterns during the protocol. The grasp patterns documented during the assessment were later verified via review of the session video by a second rater.

2.3.4. Data handling and analysis

Writing samples were anonymized and handwriting speed and legibility were scored by two independent, experienced raters (one being the primary author). Intra-rater reliability of 0.81 for the primary author and inter-rater reliability rating of 0.93 were achieved. The primary author and a second independent rater reviewed the videos. Inter-rater reliability for grasp classification was 0.82. Intra-rater for the primary author was 0.80.

Data analysis was conducted using Matlab 7.9.0 and Statistical Analysis Software (SAS 9.2) programs. Descriptive statistics on the distribution of grasp patterns were computed. To examine the effect of grasp pattern on speed and legibility, multiple linear regression (MLR) analysis as described by Armitage, Berry & Matthews (2008) was invoked. This method extends ANOVA to models with continuous variables. Legibility and speed were dependent variables while grasp was the independent variable. We controlled for gender, handedness, school, teacher and time of assessment (spring or fall) in the model. A secondary analysis using Chi-Square was conducted to examine the relationship of school, gender, handedness, teacher and time of assessment on grasp pattern and legibility and speed. Pearson's correlation coefficient was used to test the association between the CHES quality and the HPSQ scores.

2.4. Results

2.4.1. Sample Characteristics

The mean age of the participants was 9 years 11 months (± 4.32 months) and the sample was almost equally divided between boys and girls with 59 males and 61 females (see Table 1). Seven percent of the children in the sample were left-handed.

Table 2-1: Participants and Sample Characteristics

	Male (n=59)	Female (n=61)
Right handed	54	57
School 1	18	20
School 2	22	17
School 3	8	8
School 4	11	16
Spring assessment	50	54
Fall assessment	9	7

2.4.2. Handwriting quality and speed

Based on the criteria for manuscript letters, 19 percent of the sample scored 30 or below (poor range) and were categorized as dysgraphic. The writing speeds were calculated and ranged from 30 to 82.5 LPM. The HPSQ scores indicated that 37.5% of the sample was dysgraphic when the recommended cut-off of 14 was used, and there was only a low correlation (Pearson $r = 0.31$) between the CHES quality and the HPSQ scores.

2.4.3. Distribution of Grasp Patterns

The dynamic tripod grasp was the highest frequency grasp pattern in the sample, with 27 (23%) children but the lateral quadrupod grasp frequency was nearly identical, with 26 (22%). There was a significant relationship between grasp pattern and gender ($\chi^2(6, N = 120) = 14.15, p = 0.03$), as shown in Figure 2.2. Specifically, the distribution of lateral and dynamic grasp patterns was different between boys and girls, with the lateral grasp patterns more strongly represented in girls ($\chi^2(1, N = 120) = 10.40, p = 0.0013$). Sixty-eight percent of the boys had a dynamic grasp pattern and 65 percent of girls had a lateral grasp pattern. From the video analysis of grasps, it was observed that 24 (20%) of the participants switched grasp pattern during the writing; 12 (10%) switched between the dynamic tripod and lateral tripod while another 12 (10%) switched between the dynamic quadrupod and the lateral quadrupod. Because the participants who switched grasp did not have a consistent pattern, they were assigned their own category. Three participants used grasps that were immature and consisted of a combination of a four-fingered grasp and an interdigital grasp (Tseng, 1998). These three grasps were termed ‘Other’. All grasp patterns were included in the ensuing analysis.

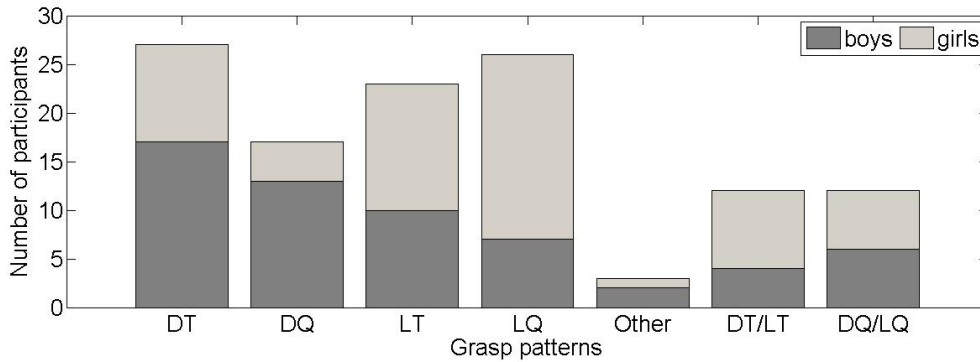


Figure 2-2: Grasp pattern distribution (DT=dynamic tripod, DQ=dynamic quadrupod, LT=lateral tripod, LQ=lateral quadrupod) The last two columns represent switching grasps.

2.4.4. Effect of Grasp Pattern on Speed and Legibility

The MLR analysis revealed no effect of grasp pattern on either legibility ($F(6, 103) = 0.95, p = 0.466$) or speed ($F(6, 103) = 0.54, p = 0.773$). Figure 2.3, shows the distribution of grasp patterns by proficient and dysgraphic participants. All three of the participants who had grasp patterns in the “Other” category, had dysgraphic writing. In addition, there was no difference in the number of boys or girls who switched their grasp pattern ($\chi^2(1, N = 24) = 1.009, p = 0.32$).

2.4.5. Effects of Gender, Time of Assessment, School, and Handedness on Speed and Legibility

Based on the MLR results, gender was significantly related to speed ($F(6, 103) = 8.36, p = 0.005$) but not legibility ($F(1, 103) = 3.57, p = 0.06$). In particular, girls wrote faster than boys (girls: 57.7 LPM; boys: 49.7 LPM), but had similar legibility scores (girls: 58.5; boys: 49.2). There was no significant relationship between grasp pattern and handedness ($\chi^2(6, N = 120) = 7.34, p = 0.29$), school ($\chi^2(18, N = 120) = 25.65, p = 0.11, df = 18$), or teacher ($\chi^2(42, N = 120) = 55.01, p = 0.12, df = 42$).

The time of assessment was significantly related to writing speed ($F(1, 103) = 7.73, p = 0.007$) with the children assessed in the spring writing faster than those assessed in the fall (spring: 55 LPM; fall: 45 LPM). However, there was no significant relationship between the legibility of the work and the time of assessment ($F(1, 103) = 0.94, p = 0.33$).

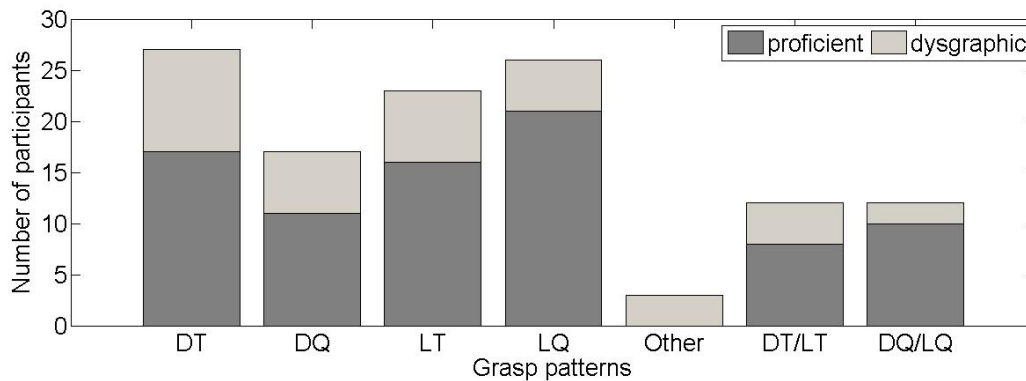


Figure 2-3: Grasp patterns of proficient and dysgraphic writers (DT=dynamic tripod, DQ=dynamic quadrupod, LT=lateral tripod, LQ=lateral quadrupod) The last two columns represent switching grasps.

2.5. Discussion

2.5.1. Occurrence of Multiple Grasp Patterns

Previous studies have identified four mature grasp patterns commonly used for writing. There is however, no consensus in the literature about the prevalence of these grasp patterns. For example, the reported prevalence of dynamic tripod grasp ranges from 67% (Summers & Catarro, 2003) and 50% (Dennis & Swinth, 2001) to 33% (Koziatsek & Powell, 2000). In the current study, each of the four grasp patterns occurred with non-trivial frequency within the sample of school-aged children. The variation in the reported prevalence of the four common grasp patterns might be explained by differences in teaching practices over time and changes in emphasis in school curricula. Currently, there is less emphasis placed on teaching handwriting in schools in North America (Graham et al., 2008).

Twenty percent of the sample switched their grasp pattern during the course of the two minute handwriting assessment; this did not, however, seem to impact the legibility or speed of the writing. This finding is corroborated by a study of university students where 28% of the sample self-reported using more than one grasp pattern during a longer writing task (Summers & Catarro, 2003). Nonetheless, the alternating grasp phenomenon has not been reported in children. With a longer writing sample, switching grasps may be a strategy to cope with pain or discomfort during writing. In particular, the students in the current study switched between a dynamic and a lateral grasp pattern, regardless of the number of fingers on the pencil. The thumb

switched from a position of opposition to a position of adduction across the top of the pencil (Summers, 2001). This may be a compensation strategy for fatigue in the hypothenar muscles (opponens pollicis and abductor pollicis brevis) that serve to maintaining thumb opposition.

2.5.2. Effect of Grasp Pattern on Handwriting Quality

While there was a relationship between grasp and handwriting with variables such as gender and time of assessment, there was none between grasp and handwriting speed or legibility, corroborating previous reports in children (Dennis & Swinth, 2001; Koziatek & Powell, 2003; Sassoon et al., 1986; Ziviani & Elkins, 1986). The thumb is opposed to the index finger in the dynamic tripod and quadrupod grasps while adducted to or crossed over the top of the index finger in the lateral tripod and quadrupod grasps. This difference in thumb position did not appear to influence the speed or legibility of the written product. These results add to the mounting body of evidence that suggests that functional writing in children can be achieved with grasps other than the dynamic tripod (Koziatek & Powell, 2003; Sassoon et al., 1986).

2.5.3. Legibility

The 19% of children identified in the present study as having poor legibility falls within the 10 to 34 % range of prevalence reported in the literature (Karlsdottir & Stefansson, 2002), but exceeds a recent estimate that 6% of students in Grade 3 have persisting dysgraphia (Overvelde & Hulstijn, 2011). The heightened level of writing difficulties in the current study could be the result of a selection bias; the study might have been more appealing to parents of children suspected of having writing difficulties and therefore, these children were more strongly represented in the sample. Or the reduced friction of writing on a tablet as compared to pencil-on-paper may also be partially responsible (Chau, Ji, Tam & Schwellnus, 2006). However, writing on a tablet with a stylus is likely becoming a familiar task to children with the proliferation of stylus-enabled handheld devices, such as portable gaming systems.

The lack of correlation between the HPSQ and CHES scores may be attributable in part to the language used in the HPSQ; some of the questions included double negatives, which may have been misinterpreted by the teachers. It is also possible that the HPSQ cut-off we borrowed from literature may need to be tailored to the collected data.

2.5.4. Speed

Our results suggest that gender significantly affects the speed of handwriting (girls wrote faster than boys). Nonetheless, the gender difference in letters per minute was quite small and may not translate into functionally different speeds during activities at school. The average printing speed was higher (spring: 55 LPM, fall: 45 LPM) than those published for similarly aged children writing in cursive (Phelps and Stemple, 1985; Koziatsek and Powell, 2003), but slower than speeds achieved by Grade 4 writers in Graham, Berninger, Weintraub and Shaffer (1998). However, in the latter, students were asked to write as quickly as possible. Further, children in the current study elected to use manuscript rather than cursive. Cursive writing is traditionally introduced in Grade 3 (Ontario Ministry of Education) and students may still be more proficient with printing by Grade 4. Graham, Berninger and Weintraub (1998) found that children in the United States who used either manuscript or a mix of manuscript and cursive wrote faster than those using cursive alone, although their sample included children in Grades 4-9 so it is difficult to compare directly with the current sample. The finding that students assessed in the spring (concluding Grade 4) wrote faster than the students assessed in the fall (beginning Grade 4) is consistent with the fact that spring students have 6 months of extra writing exposure and practice (Tseng & Chow, 2000).

While there were proficient and dysgraphic writers in each grasp category, the three participants in the “Other” grasp category were all dysgraphic writers. All three had poor legibility scores, and two had writing speeds below the average speed of the entire group. The positioning of the fingers in these grasps precluded fine distal movements of the fingers. Thus, letter formation was achieved via wrist movements. This observation resonates with literature on the static tripod, a grasp which relies heavily on the forearm and shoulder muscles to form letters (Long et al., 1970; Rosenbloom & Horton, 1971). While this sample was too small for statistical analysis, future comparisons of writing speed and legibility between mature/dynamic and immature/static grasp patterns are warranted.

2.5.5. Limitations

Recall that children chose to print rather than write cursively. Given that no assessments exist for evaluating manuscript writing in the advanced grades (Feder & Majnemer, 2003), legibility was

scored using the CHES-M criteria and speed was calculated in letters per minute. Though the CHES lacks both published information concerning validity and test-retest reliability, it was the only assessment that investigated both manuscript and cursive with the same tool. While we used a percentile cut-off (Graham et al., 2006) to facilitate interpretation of legibility scores, rate scores could not be norm referenced due to the fact that the chronological age of our sample exceeded the CHES-M prescriptions; writing speed is known to increase as children age and progress through school (Graham, Weintraub & Berninger, 1998). A number of teachers indicated that they do not require assignments in Grade 4 in cursive format, so existing assessments may need to be adapted to suit the changing teaching practice.

Our sample was larger than that of many previous grasp comparison studies, had an equal representation of boys and girls and contained the expected proportion of left-handed students. Our sample also may have included children with developmental disabilities such as learning disabilities or developmental coordination disorder because these children were not excluded from the sample. Nonetheless, our sample was a volunteer one, and thus may not have been representative of the general population of Grade 4 students. The schools were situated in middle and upper middle class neighbourhoods and likely did not represent all schools within the board.

Finally, 20% of our sample alternated grasp patterns during the task; a phenomenon previously observed in adults, but one that has never been quantitatively characterized. Future studies of the biomechanics of alternating grasps would shed more light on the functional equivalence of the different grasp patterns.

2.6. Conclusions

- This study presented evidence of multiple functional grasp patterns for writing in a cohort of Grade 4 children.
- There were no differences in speed or legibility among four mature grasp patterns.
- The increased legibility and speed reported for girls, who as a group predominantly employed lateral grasp patterns, further suggested that a variety of different grasps may facilitate the finger movements necessary to produce legible letters at functional speeds.

- In light of our results, occupational therapists and educators may reconsider the need for changing a child's pencil grasp when one of the four mature grasp patterns has been adopted.

2.7. Acknowledgements

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Chapter 3

The Effect of Pencil Grasp on the Speed and Legibility of Handwriting after a ten-minute copy task in Grade four children.

Submitted manuscript reference

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3. The Effect of Pencil Grasp on the Speed and Legibility of Handwriting after a ten-minute copy task in Grade four children.

3.1. Abstract

Aim: To investigate the impact of common pencil grasp patterns on the speed and legibility of handwriting after a 10-minute copy task, intended to induce muscle fatigue, in typically developing children and in those with dysgraphia.

Methods: 120 Grade 4 students completed a standardized handwriting assessment before and after a 10-minute copy task. The students indicated the perceived difficulty of the handwriting task at baseline and after 10-minutes. The students also completed a self-report questionnaire regarding their handwriting proficiency upon completion.

Results: The majority of the students rated higher effort after the 10-minute copy task than at baseline (rank sum: $p=0.0001$). The effort ratings were similar for the different grasp patterns (multiple linear regression: $F=0.37$, $p=0.895$). For both typically developing children and those with dysgraphia, the legibility of the writing samples decreased after the 10-minute copy task but the speed of writing increased.

Interpretation: The quality of the handwriting decreased after the 10-minute copy task; however, there was no difference in the quality or speed scores among the different pencil grasps before and after the copy task.

What paper adds: The dynamic tripod pencil grasp did not offer any advantage over the lateral tripod or the dynamic or lateral quadrupod pencil grasps in terms of quality of handwriting after a 10-minute copy task. These four pencil grasp patterns performed equivalently. Our findings question the practice of having students adopt the dynamic tripod pencil grasp.

3.2. Introduction

Handwriting is an important functional skill for school-aged children. In primary school, children are required to write with pencil and paper for a large part of their schoolwork as well as for tests and notes, although some of the burden of writing has been alleviated by computers (Graham, et al., 2008). Longcamp et al., (2008) recently argued that unlike keyboarding, the memory of motor actions involved in letter writing has a significant impact on the long lasting recognition of shapes and letters. Letters learned by hand are recognized more accurately and for longer periods and can be distinguished from mirror images better than letters learned by keyboarding (Longcamp et al., 2008). Thus, the importance of learning handwriting should not be underestimated.

The majority of children learn to write in the first few grades of school; however, an estimated 3-27% of these children have difficulty with this essential task (Graham, Berninger, Weintraub, & Schafer, 1998; Smits-Engelsman et al., 2001). When a typically developing child has handwriting difficulties, the condition is often termed dysgraphia (Feder & Majnemer, 2007; Maeland, 1992). Poor handwriting performance, namely reduced speed and legibility, has been linked to decreased self-esteem and lower academic achievement (Graham et al., 1998). To assist these children, they are frequently referred to school-based occupational therapists (OTs) (Overvelde & Hulstijn, 2011).

3.2.1. Handwriting and Pencil Grasp

Poor pencil grasp has commonly been the target of intervention by both teachers and OTs, who attempt to alter the child's pencil grasp from anything different from the traditional dynamic tripod grasp (Feder & Majnemer, 2007; Graham et al., 2008). Schneck (Schneck, 1991) found that poor writers had less mature pencil grasps, though later research failed to replicate these results (Tseng, 1993). A dynamic or mature pencil grasp, specifically the dynamic tripod grasp, has been suggested as the best grasp for writing because it allows for efficient distal movements of the pen or pencil (Elliott & Connolly, 1984) and purportedly minimizes muscle tension that can lead to fatigue (Tseng & Cermak, 1993; Ziviani, 1983). In contrast, a static or immature pencil grasp is one where the pencil is held by the fingers, but the movement of the pencil is

controlled by the extrinsic muscles of the hand and arm, while the fingers remain static (Elliott & Connolly, 1984).

There are at least four pencil grasp patterns that are mature and therefore functional for handwriting: the traditional dynamic tripod grasp and three other grasps, including the lateral tripod grasp; the dynamic quadrupod grasp and the lateral quadrupod grasp (Tseng & Cermak, 1993; Ziviani, 1983). Although the name of the lateral grasps does not imply dynamic movement, in these mature grasps, the fingers are dynamic and supply movement while the thumb is static (Elliott & Connolly, 1984). Performance was similar for these grasps for short duration copy tasks, where the speed and legibility of the written output was not significantly different (Schwellnus et al., 2011). The three other grasps may require excessive effort to maintain over longer periods of writing. With the dynamic tripod grasp, the distal control of the movement allows the muscles to have consistent pressure on the pencil and therefore minimizes muscle tension, which can lead to muscle fatigue (Soechting & Flanders, 2008). Although writing is a low force activity, fatigue has been reported in the muscle groups involved in grasping a pen during writing for 10-minutes (Parush et al., 1998). This is due to the isometric muscle effort expended to control the many joints involved in maintaining the grasp of the pencil during writing, and this effort can lead to fatigue over time (Udo, Otani, Udo, & Yoshinaga, 2000).

3.2.2. Pencil Grasps and Muscle Fatigue

The four mature grasp patterns use similar groups of muscles in the hands and forearm and involve intrinsic muscle function necessary for fine manipulation of the writing utensil to form letters (Long, Conrad, Hall, & Furler, 1970). Increased effort is proposed to lead to fatigue (Ziviani, 1983) and over longer writing tasks has been recognized as a factor that affects the quantity and quality of written output of children and adults (Dennis & Swinith, 2001; Tseng & Cermak, 1993). The amount of effort required to write becomes even more significant as children progress through school and the length of assignments increases (Cornhill & Case-Smith, 1996).

Stevens (2008) conducted a study comparing the dynamic tripod, lateral tripod grasp and a group of all other grasp patterns in adults. The participants copied until they could not write

anymore. The group with the lateral tripod grasp wrote the same number of words but stopped writing (were fatigued) earlier than the other two groups. The author suggested that while the lateral tripod grasp was functional, this grasp may be more susceptible to fatigue than the other grasp patterns. In a similar vein, Dennis and Swinth (2001) evaluated the impact of task length (short versus long writing task) and pencil grasp (dynamic tripod versus atypical grasps) on the legibility of children's writing. The "atypical grasps" category included all the other functional writing grasps such as the dynamic quadrupod, the lateral tripod and the lateral quadrupod and any other writing grasp observed. Although the legibility of the short tasks was better than that of the long tasks, they did not find that grasp pattern impacted speed or legibility, nor was grasp type influenced by task length (Dennis & Swinth, 2001). Due to the modest study sample, the group with "atypical" grasp could not be further subdivided for finer grained analyses. In addition, the authors did not use a standardized handwriting assessment, and in fact, varied the task among participants, precluding comparisons to other studies and confounding the between-group analyses. Parush, Pindak, Markowits and Karsenty (1998), evaluated children's handwriting quality and writing speed before and after a 10-minute copy task. This task duration was selected through teacher consultation as being sufficient to induce physical fatigue. Parush and colleagues monitored the stability of the pencil grasp pattern (whether the child maintained or changed grasp pattern) but did not identify the type of pencil grasp utilized, nor was fatigue specifically measured. The quality of the writing of both the proficient and the dysgraphic groups decreased after the 10-minute copy task; however, writing speeds of both groups increased. Overall, the study suggested that children take breaks when writing for prolonged time, but made no recommendations regarding pencil grasp.

The systematic investigation of the impact of fatigue and pencil grasp on the quality of handwriting is necessary because children write for increasingly longer times as they progress through school (Reid, Chiu, Sinclair, Wehrmann, & Naseer, 2006). Muscle fatigue, often associated with heavy exercise, is defined as an "acute impairment of performance that includes both an increase in the perceived effort necessary to exert a desired force and an eventual inability to produce this force" (Barry & Enoka, 2007, pp. 465). Without rest, debilitating fatigue can result in the deterioration of both the quality as well as the speed the task performed. In studying the impact of fatigue on handwriting, Provins (1989) occluded blood flow to the writing arm, which resulted in deterioration of both the speed and quality of handwriting.

The measurement of muscle fatigue in low intensity activity is challenging, particularly in young children due to its abstract and subjective nature. Review of the current literature revealed little information on the measurement of fatigue during a specific low intensity activity. Most studies quantified overall body fatigue in children with a degenerative disease or cancer, neither of which is applicable to the current investigation. The literature on perceived effort or exertion has focused, for the most part, on healthy children. Perceived effort refers to the subjective difficulty of a task, which is of interest in the current handwriting study and consistent with the definition of fatigue above. There are a number of perceived exertion scales valid for young children (Gros Lambert, Hintzy, Hoffman, Dugué, & Rouillon, 2001). From the literature, children from 8-14 are able to assess their perceived effort (Gros Lambert et al., 2001). A scale with the combination of pictures and words works best with children (Yelling, Lamb, & Swaine, 2002), and children do best when they have explicit instructions as to how to use the scale, although the depicted activity does not necessarily have to be the same as the activity performed (Eston, 2009).

Further research is needed to investigate two aspects of increased writing. The first is whether pencil grasp, specifically the dynamic tripod, the dynamic quadrupod, the lateral tripod and the lateral quadrupod, are impacted by a prolonged writing task. These four grasps have been found to produce equally functional writing over a short duration of time (Schwellnus et al., 2011). The second aspect needing further investigation is whether or not longer writing tasks impact the functionality of the chosen pencil grasp, in terms of speed and legibility of writing. The objective of the current study was to investigate the impact of pencil grasp on the speed and legibility of the writing before and after a long copy task.

3.3. Methods

3.3.1. Participants

A volunteer sample of 120 Grade 4 students was recruited from a local municipal school board. The Research Ethics Boards of the school board and the local university approved the study. Written consent was obtained from parents of study participants and verbal assent was obtained from the children at the time of the study. The children were enrolled in four schools in a fairly

close geographic area in a metropolitan city. The school neighbourhoods were considered to be middle to upper middle class based on socioeconomic status of the school catchment area. Eight teachers consented to the study in their classes.

3.3.2. Protocol and Instruments

The participants were tested in a small quiet room within the school during regular school hours. Most assessments occurred at the end of the spring term; however, a new cohort of 16 Grade 4 children was tested in the fall of the subsequent school year. The participants were seated on a height adjustable chair at a regular school table. They were initially positioned with their feet supported on the floor or the footplate of the chair. The children were videotaped with a Sony Digital Video Recorder from the non-dominant side for a sagittal view of the writing session.

The children completed a standardized writing assessment, the Children's Handwriting Evaluation Scale or CHES, twice, before a copy task (time 1) and again after the copy task (time 2) (Phelps, Stemple & speck, 1985). The manuscript version (CHES-M) is available for students in Grades 1 and 2 while the cursive version (CHES) is suited to children beyond Grade 2. Both assessments evaluate handwriting speed and legibility on the basis of two minutes of writing with pencil and paper, namely, copying two sentences for the CHES-M and five for the CHES. Both versions have excellent psychometric properties (intra-reliability of 0.82 and inter-reliability of .95) (Phelps, Stemple, & Speck, 1985). There is no published validity for the CHES, nor is there test-retest reliability data available. Children are identified as requiring remediation if they score poorly (see below) on at least one of speed or legibility.

In the current study, all students chose to write in manuscript form. Because there is no standardized handwriting assessment for manuscript writing for Grade 4 students, CHES-M legibility criteria were used for scoring the legibility of the writing. Grading criteria from a standardized handwriting assessment have been applied to non-standardized writing material (Dennis & Swinth, 2001). The ten criteria are scored for each writing sample and a raw score calculated out of 100 in increments of 10. A quality score of 80-100 indicates good legibility; a score of 50-70 indicates satisfactory legibility and a score of 40 or below indicates poor legibility signalling the need for remediation. Because the age of the current sample was higher than that of the CHES-M norms for legibility, the 15th percentile for our sample was used as a cut-off for

dysgraphia, which resulted in a threshold score of 30 instead of the reported 40 (Graham et al., 2006). Speed of writing is dependent upon the method of writing, and norms for higher grades are based on cursive writing style, which eliminated the comparison to the speed norms (Graham, Struck, Santoro, & Berninger, 2006; Karlsdottir & Stefansson, 2002). The number of letters per minute (LPM) was calculated from the sample.

Participants wrote all aspects of the protocol with an instrumented pen on a self-inking Wacom Cintiq 12WX tablet connected to a laptop computer. The tablet was approximately 0.5 inch thick and had a 10.3 inch x 6.4 inch screen. The tablet was positioned in the landscape position. Each participant had one minute to practice free writing on the tablet. They then copied the CHES (Phelps, J. Stempel L., 1987) before and after a 10-minute copy task written at 4th Grade literacy level. A 10-minute duration has been shown to induce fatigue in children (Parush et al., 1998). As the participants wrote on the tablet, they tapped a scroll button on the bottom menu bar to move the written text up and obtain new writing space.

Measurement of fatigue during handwriting can be challenging. Existing measures of perceived fatigue are often not designed for children. In this study, we used the Perceived Children's Effort Rating Table (PCERT) (Yelling et al., 2002), which has established validity for children 9 - 15 years of age (Yelling; Marinov, Mandadjieva, & Kostianev, 2008). The PCERT is a pictorial rating scale from 1-10; the participants identify the number associated with their perceived level of exertion. This measure does not directly measure fatigue, but is an indication of perceived effort associated with the writing task. Children rated their level of perceived effort with the PCERT at three different times: at baseline before any writing (T1), after the first CHES (T2), and again after the 10-minute copy task (T3). They were instructed to rate how much effort they had expended to complete the specified amount of writing, noting any muscle pain that was experienced.

3.3.3. Data Handling and Analysis

The participants' writing samples were stripped of all identifying data and scored for handwriting speed and legibility in random order by the primary author who is a registered and experienced OT. The random presentation removed any bias resulting from knowledge of segment ordering by the rater. An intra-rater reliability of .81 was achieved. Inter-rater reliability

of .93 was achieved with a second, equally experienced rater for 15 randomly selected samples of writing. An inter-rater reliability of .82 was achieved for the classification of pencil grasp pattern based on 35 of the participant videos scored by the same two raters. Intra-rater for the primary author for grasp classification for 10 students from video was .80.

Matlab version 7.9.0 and Statistical Analysis Software (SAS) version 9.2 were used for data analysis. Multiple linear regression (*Statistical Methods in Medical Research*, 2008) was used to evaluate the relationships between the change in perceived effort (dependent variable) and grasp pattern while controlling for writing proficiency as measured by CHES legibility scores at time 1 (T1). The following additional independent variables were included in the model: gender, handedness, school, and time of assessment (spring or fall). Teacher was initially included but was not significant and subsequently removed from the model. To evaluate the significance between the PCERT scores, we used the Wilcoxon rank-sum test, as the data were not normally distributed. To test the change in the CHES legibility and speed scores between T1 and T2, a paired t-test was used. A Chi-Squared test was used to test the relationship between the PCERT scores of girls and boys. Unless otherwise specified, a significance level of 5% was used in statistical testing.

3.4. Results

3.4.1. Sample demographics

The volunteer sample of 120 participants was almost equally divided between girls and boys, with 49% boys and 51% girls. Seven percent of the samples were left handed writers, which is within expectations for dominance (Vuoksima, Koskenvuo, Rose, & Kaprio, 2009). The participants had a mean age of 9 years 11 months. The students used four common grasps: the dynamic and lateral tripod as well as the dynamic and lateral quadrupod grasps. In addition, three other grasp categories were observed: a combination of the four-fingered grasp and the interdigital grasp (Tseng, 1998), a grasp which alternated between the dynamic tripod and the lateral tripod, and a grasp which alternated between the dynamic quadrupod and the lateral quadrupod. The distribution of the grasp patterns is depicted in Figure 1 below.

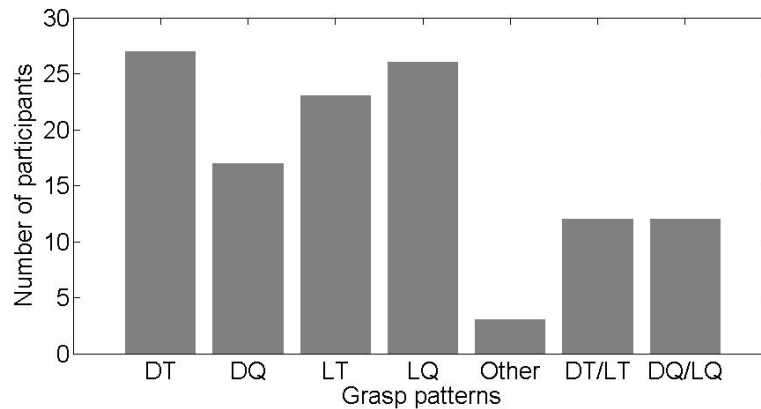
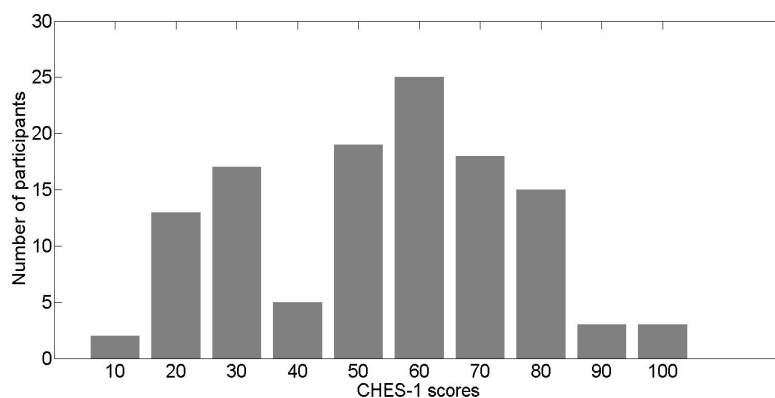


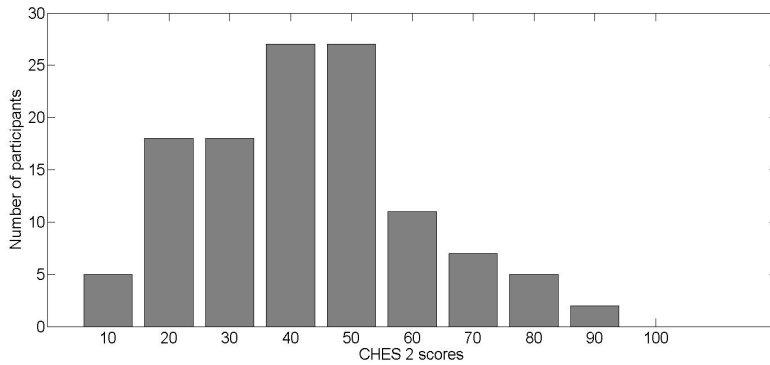
Figure 3-1: Distribution of grasps by participants

3.4.2. Legibility

Recall that legibility was scored according to the CHES-M criteria. Within-participant comparisons were based on raw scores only. The legibility scores for the CHES before and after the 10-minute copy task are shown in Figure 2. Legibility generally decreased after the fatigue task. Nineteen percent of the sample had poor legibility (score of 30 or below) before the 10-minute copy task; however, after the copy task, 34% of the participants' writing was of poor legibility. The CHES scores at T1 and T2 were statistically different (t-test $p < 0.0001$). The children wrote slightly more at T2, 56 vs. 54 LPM (t-test $p = 0.03$).



(a) CHES 1.



(b) CHES 2.

Figure 3-2: Distribution of CHES 1 (a) and CHES 2 (b) scores

3.4.3. Perceived effort

The PCERT scores at T1, before any writing, and after the 10-minute copy task, i.e., at T3, were significantly different. Before the fatigue task the median rating was three; after the fatigue task the median rating was four (rank sum: $p=0.0001$).

3.4.4. Grasp pattern

The multiple linear regression analysis revealed no significant differences in PCERT scores when compared by grasp pattern ($F=0.49$, $p=0.813$), while controlling for proficiency within the model. Twenty participants increased their scores in legibility; however, only one of those participants decreased their PCERT scores, or indicated that they were less fatigued after the 10-minute copy task. The covariates were included in the model, with significant relationships found for calendar date of assessment, $F=9.55$, $p=0.003$ (those from the fall had higher scores than those in the spring). Gender ($p=0.062$), school ($p=0.194$), and handedness ($p=0.026$) were not significant when the Bonferroni correction was applied due to the number of comparisons, and the level of significance lowered to $p=0.008$.

3.5. Conclusion

3.5.1. Impact of perceived effort on different pencil grasp patterns

We investigated the influence of perceived effort on the common grasp patterns. We found that grasp did not significantly affect perceived effort. In this study we used a 10-minute copy task to induce fatigue. The 10-minute copy task did appear to serve its purpose; the PCERT scores for perceived effort increased after the 10-minute copy task ($p=0.0001$). The fact that there was no difference in rating of perceived effort between the children using the different pencil grasps may be due to the fact that the muscles involved in the different types of grasp are very similar, and therefore the grasps may have been equally affected by the long copy task.

3.5.2. Impact of perceived effort on legibility and speed of writing

The legibility of the writing samples decreased after the 10-minute writing task ($p<0.0001$) across the entire sample, with no significant differences between the four grasp patterns. Previous explanations for decreased legibility with prolonged writing have included the natural tendency for individuals to write faster as time goes on (Udo et al., 2000) and diminishing interest in the writing task (Parush et al., 1998). Indeed, in the present study, we observed a speed increase accompanied by a decrease in legibility, which could be a manifestation of the speed-accuracy trade off in handwriting (Weintraub & Graham, 1998). Legibility may have also decreased, in part, as a consequence of the overall tiredness that children reported.

All students wrote in manuscript, though traditionally by 9-10 years of age, cursive would be the expected style of writing in North America (Graham et al., 1998). A trend of continued use of manuscript has been reported by Graham, Weintraub and Berninger (1998), however, only 31% of their sample used manuscript by Grade 4. In the current study, the difference in writing speed increased by 2 letters per minute (from 54 to 56), which although significantly different, is not likely to translate into a functional difference in terms of writing in the classroom. Although the average writing speed for the current study was higher (55 LPM) than the some rates published for cursive by Phelps & Stemple (Phelps & Stemple, 1987) and Koziatsek & Powell (2003); it was slower than the rates published by Graham, Berninger, Weintraub and Shaffer (1998). Given

the high prevalence of manuscript, newer handwriting assessments accommodating both cursive and manuscript for older children may need to be developed.

The aforementioned speed increase occurred uniformly for all grasp patterns, possibly as compensation for fatigue (Kushki, Schwellnus, Ilyas, & Chau, 2011; Parush et al., 1998). This lack of relationship between writing speed and pencil grasp contradicts Stevens (2008), who found that in an extended writing task, participants with the lateral tripod grasp wrote for shorter durations than those with a dynamic tripod grasp. Key differences between the studies may in part account for this contradictory finding. Stevens studied adults rather than children and her participants wrote for considerably longer periods of time (up to an hour). Although the 10-minute task increased effort ratings, some children's ratings did not change so future research could investigate the impact of a longer copy task.

3.5.3. Impact of perceived effort on gender and timing of assessment

The ratings for effort did not vary by gender, with girls and boys having similar ratings for effort exerted over the writing time. The literature is divided on the issue of gender differences in perceived effort (Hutchinson & Tenenbaum, 2008). The sample was not split evenly between right and left handed children, with only 7% of the sample being left-handed, but there was no relationship between perceived effort and handedness such that the left and right handed students were similarly affected.

There was a significant effect of the season of assessment (spring vs. fall), with those in the spring having lower scores on perceived effort than those in the fall. The students in the spring had been writing for seven months at the Grade 4 level and may have simply been more accustomed to writing for 10-minutes than their counterparts just starting Grade 4. The perceived effort results did not vary by school or by teacher. This is perhaps not surprising, given that all teachers are required to follow a standard curriculum for written communication.

Overall, it appears that the different pencil grasp patterns were not affected by the 10-minute writing. The tripod grasp had been recommended as the best pencil grasp based on the well-coordinated movements from the interphalangeal joints and those of the hand and forearm (Benbow et al., 1992). Further, literature has suggested that other grasp patterns commonly

observed, including the dynamic quadrupod, lateral tripod and lateral quadrupod, may be more effortful. Our results do not support this conjecture. Neither speed nor legibility of writing was affected by these grasp patterns (Schwellnus et al., 2011). Our volunteer sample was derived from schools situated in middle and upper middle class neighbourhoods and thus may not be fully representative of grade 4 children and therefore may not be applicable to all school children. In general, the dynamic tripod grasp may be recommended for children when commencing writing, but should a child have difficulties with his or her writing, the occupational therapists should first confirm the grasp being utilized. If the grasp pattern is either the dynamic tripod, dynamic quadrupod, lateral tripod or lateral quadrupod, the therapist should look beyond the pencil grasp in pinpointing the writing issue. Instead of targeting pencil grasp, remediation may focus on improving writing quality or speed.

3.6. Acknowledgements

We would like to thank Dr. A. Dupuis and S. Klejman for their assistance with the statistical analysis as well as the staff and students and parents who took part in the study. The project was funded by; the Home Care Research Doctoral Training Award, National Grants Program, SickKids Foundation, Canada Research Chairs Program, the Natural Sciences and Engineering Research Council of Canada and the Graduate Department of Rehabilitation Science, University of Toronto.

Chapter 4

The writing forces associated with four pencil grasp patterns in children with and without dysgraphia

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4. The writing forces associated with four pencil grasp patterns in children with and without dysgraphia

4.1. Abstract

Objective

To investigate the impact of pencil grasp patterns on grip and axial forces, and speed and legibility of handwriting after a ten-minute copy task.

Methods

Seventy-four Grade 4 students completed a handwriting assessment before and after a copy task. The grip and axial forces were obtained. Multiple linear regression was used to analyze the relationship between grasp pattern and grip and axial forces.

Results

When grasps were considered individually or by the number of fingers on the barrel, there was no effect of grasp pattern on forces. However, there were force differences when grasps were grouped according to the thumb position, with the adducted grasps having higher mean grip and axial forces

Conclusion

Only thumb position had a significant effect on grip and axial forces when writing. The higher axial force could provide increased stability, compensating for the loss of opposition. Despite the force differences found, the handwriting speed and legibility were not significantly different.

4.2. Introduction

4.2.1. Importance of handwriting

Handwriting is a skill that school-aged children are required to master during the early years of their education (Smits-Engelsman, Niemeijer & Van Galen, 2001). Even with the increased use of computers and tablets, handwriting is still an important skill to learn because the motor action

of creating letters on paper has been found to increase the memory of letters compared to keyboarding (Longcamp et al., 2008). James (2010) found that the creation of letter-forms augmented the visual processing of letters in preschool children. So the importance of learning to create letters cannot be underestimated.

4.2.2. Handwriting and dysgraphia

The production of functional handwriting depends on the complex interplay of a number of abilities including skillful fine motor coordination and precise force regulation as well as cognitive, perceptual and language skills (Van Galen, 1991). Understandably, given the need for this complex integration of skills, learning to write can be challenging for children. When a child has handwriting difficulties without a diagnosis of a neurological or intellectual disability, the handwriting difficulties are often termed dysgraphia (Feder & Majnemer, 2007). Dysgraphia is characterized by difficulty producing legible writing and/or keeping up with the quantity and speed of writing in their class. The number of typically developing children who struggle with handwriting varies, with reported prevalence world wide ranging from 10% to 34% (Graham, Weintraub & Berninger, 1998; Smits-Engelsman et al., 2001); however, in 2011, the prevalence among children in the eastern part of Netherlands was found to be significantly lower at 6% in Grade three (Overvelde & Hulstijn, 2011) when those with temporary dysgraphia are eliminated.

As children progress through school, they are required to write for increasing periods of time (Cornhill & Case-Smith, 1996). Previous research has recognized that fatigue involved in longer writing tasks affects the amount and quality of written output of children (Dennis & Swinth, 2001; Tseng & Cermak, 1993). However, most research conducted with children with and without handwriting difficulties has utilized a standard handwriting assessment, which only uses short samples of writing (Tseng & Cermak, 1993) and therefore does not assess the potential impact of fatigue.

4.2.3. Handwriting and pencil grasp

Pencil grasp pattern is a commonly maligned component of handwriting problems, though this belief is not evidence-based (Graham et al., 2008; Rigby & Schwellnus, 1999; Rosenblum, Dvorkin & Weiss, 2006). Historically, the dynamic tripod pencil grip has been promoted as the

optimal grasp pattern as it allows for the fine dexterous movements of the fingers to create the lines that make up letters (Elliott & Connolly, 1984). Therapists and teachers commonly recommend that children, especially those with handwriting difficulties, use a dynamic tripod pencil grasp (Schneck & Henderson, 1990). Three other pencil grasp patterns, namely, the dynamic quadrupod, the lateral tripod and the lateral quadrupod pencil grasps, are suggested to be mature grasps that are functional for writing. The prevalence of each of these grasp patterns in children is comparable to that of the dynamic tripod grasp (Koziatek & Powell, 2003; Schwellnus et al., 2011 in press). In mature pencil grasps, the intrinsic muscles of the hand are responsible for the movement of the pencil within the hand (Elliott & Connolly). In contrast, with immature pencil grasp patterns, the pencil is held with the fingers but the movement is controlled by the extrinsic muscles (Elliott & Connolly).

4.2.4. Pencil grasps patterns and grip and axial forces

Pencil grasps are commonly classified according to the position of the thumb, the number of fingers on the barrel of the pencil and finger joint position. In the dynamic grasps, the thumb is in a position of opposition; the thumb and fingers are placed on opposite sides of the pencil. In the lateral grasp patterns, the thumb crosses over the pencil, stabilizing the utensil against the other fingers. However, the pad of the thumb tends to contact the lateral border of the index finger instead of the shaft of the pencil. The number of fingers in contact with the barrel is three in a tripod grasp and four in a quadrupod grasp. The dynamic grasps with the opposed finger positioning are deemed to be balanced or stable grasps because the forces exerted by the three (or four) digits intersect at a common point and therefore require minimal force to maintain (Soechting & Flanders, 2008). Grasps have also been categorized by the amount of hyperextension of the distal finger joints of the index finger (Selin, 2003; Ziviani, 1983), as a proxy for grip force, representing the force applied by the fingers on the barrel of the pencil.

The amount of surface contact with the pencil barrel varies with the different finger and thumb positions of the four grasp patterns. In the quadrupod grasps, there is an additional finger in contact with the barrel and with the lateral grasps, the adduction of the thumb reorients the pencil within the grasp and increases the barrel to finger contact area. (Figure 4.1). The impact of this greater surface contact area on grasp function is unknown. It has been hypothesized that grasps

other than the dynamic tripod may decrease the amount of force exerted by each digit by distributing the requisite force over a larger surface area. Alternatively, the broadened surface contact may increase the total grip force, rendering the grip more static, and in turn diminish the engagement of the intrinsic hand muscles (Dennis & Swinth, 2001). While the former hypothesis suggests that the grasp with more contact points would be more stable; the increased stability was not found to be advantageous for writing though it may help to reduce fatigue (Wu & Luo, 2006). The broader surface area hypothesis suggests that grasp patterns with increased contact and pressure are less functional than the dynamic tripod grasp; the elevated pressure over time would increase the effort required to maintain the grasp, inducing premature fatigue, which in turn would decrease motor control and the legibility of writing (Dennis & Swinth; Engel-Yeger & Rosenblum, 2010; Tseng & Cermak, 1993;). In fact, the lateral tripod grasp has been linked to earlier fatigue (Stevens, 2008).



Dynamic Tripod



Dynamic Quadrupod



Lateral Tripod



Lateral Quadrupod

Figure 4-1: Four mature grasp patterns

In addition to grip force, axial force can also be impacted by the pencil grasp pattern. Axial force, also termed point pressure, is the force applied downward from the writing utensil onto the writing surface (Harris & Rarick, 1957). Increased variability of axial force has been associated with decreased legibility of writing (Harris & Rarick, 1959; Baur et al., 2006). With greater surface contact area, the impact on the axial force is unknown; it may remain the same, increase or decrease depending on the number of digits involved and their orientation with respect to the barrel of the writing utensil.

4.2.5. Pencil grasp patterns and fine dexterous finger movement

In addition to minimizing grip force, another desirable feature of the dynamic tripod pencil grasp is the facilitation of fluid and fine movements of the three fingers as they flex and extend to form vertical and curved letter strokes (Elliott & Connolly, 1984; Tseng, 1993). In addition, the ring and the fifth fingers provide stabilization against the palm and support the metacarpal phalangeal arch of the hand (Benbow, 2002; Ziviani, Wallen, Henderson, & Pehoski, 2006). The increased surface area of grasps other than the dynamic tripod could decrease the dynamic movement of the pencil (Dennis & Swinth, 2001). With the lateral grasps, the thumb is adducted and the web space is closed more tightly around the barrel of the pencil, which restricts the movement of the

pencil, eliminates thumb opposition and further compromises balance (Dennis & Swinth). Likewise, with the dynamic quadropod grasp, the ring finger is in contact with the pencil barrel, thereby eliminating the radial/ulnar dissociation of the fingers. In turn, stabilization normally provided by the ring and fifth fingers against the palm of the hand (as in the dynamic tripod grasp) is lost (Ziviani, Wallen, Henderson & Pehoski, 2006). The vertical movements of the pen are therefore provided solely by the movement of the index, middle and ring finger, and the thumb is minimally involved in the movement of the pencil. The aforementioned movement restrictions may reduce the variability of grip force. Indeed, previous research has found that the when the grip force has a low amount of variability, the quality of the handwriting is decreased (Falk, Tam, Schwellnus & Chau, 2010).

For a pencil grasp to be functional for writing it must offer the user the ability to efficiently create a legible written product for the required duration. Children must be able to write long enough to keep up with class work and to complete assignments and examinations as they progress through school. Stevens (2008) found that people who used the lateral tripod grasp stopped writing earlier than those using other grasps, though they were able to produce the same amount of work. It was suggested that the dynamics of this grasp might cause earlier fatigue due to inefficient movements that are controlled proximally (Summers, 2001).

No previous studies have examined the interaction between the axial force on the writing tablet and the grip forces with different pencil grasp patterns. With forces potentially impacting the endurance of the grasp, as well as the speed and legibility of the writing, it is important to determine whether these four grasp patterns are kinetically similar in an extended writing task. A ten-minute duration of the copy task was previously found to be sufficient to fatigue Grade 3 students (Parush, Pindak, Hanh-Markowitz, & Mazor-Karsenty, 1998) and this duration of writing did significantly alter scores for perceived effort (Schwellnus et al., in press).

This study investigated differences in grip and axial forces both before and after a ten-minute copy task in Grade 4 children to test whether the four mature grasp patterns are equally functional for handwriting. Also investigated was the dynamic movement of the grasp patterns, key for writing functionalis, by examining grip force variability of the four grasp patterns. The grasps were analyzed in three different groupings because the number of digits involved and the

position of the thumb may impact the forces and the dynamic nature of the movement of the pen. Initially, grasps were all compared to each other. Subsequently, grasps were grouped according to the number of fingers on the barrel (tripod or quadrupod) and finally by the position of the thumb (lateral versus dynamic).

To test whether the four mature grasp patterns are equally functional for handwriting, this study investigated differences in grip and axial forces both before and after a 10-minute copy task in Grade four children. The 10-minute duration of the copy task was previously found to be sufficient to fatigue Grade 3 students (Parush, Pindak, Hanh-Markowitz, & Mazor-Karsenty, 1998) and this duration of writing did significantly alter scores for perceived effort (Schwellnus et al., 2011). The dynamic movement of the grasp patterns was also investigated by examining grip force variability of the four grasp patterns. The grasps were analyzed in three different groupings because the number of digits involved and the position of the thumb may impact the forces and the dynamic nature of the movement of the pen. Initially, grasps were all compared to each other. Subsequently, grasps were grouped according to the number of fingers on the barrel (tripod or quadrupod).

4.3. Methods

4.3.1. Participants

One hundred and twenty grade four students were recruited as a volunteer sample from four schools within a metropolitan school board. Based on the statistics from the schools postal codes, the average household income for the school catchments were in the middle and upper middle classes based on Statistics Canada (statcan.gc.ca). Both the school board's and the university's Research Ethics Boards approved the study. Written consent from each parent was obtained and each child assented to participate at the time of data collection. Handwriting is relatively well developed by Grade four, and the quality of writing has stabilized (Overvelde & Hulstijn, 2011). The students had been introduced to cursive writing and are old enough to write for a minimum of ten minutes (Dennis & Swinith, 2001; Parush, et al., 1998). Data collection was conducted in the spring for most of the students; however, to achieve the desired sample size, an additional sixteen students were recruited in the subsequent school year. These new recruits were derived

from a new cohort of Grade 4 students and were assessed in the fall (thus they were younger and less experienced writers than the spring cohort at the time of testing).

Instruments

4.3.2. Writing pen and tablet

To evaluate the grip and the axial forces, the students wrote with an instrumented pen on an electronically inking, pressure sensitive digitizing tablet (Wacom Cintiq 12WX). The dimensions (width x height x thickness) of the tablet were 10.3 x 6.4 x 0.67 inches (261.6 mm x 162.6 mm x 11 mm). In the landscape orientation, the writing surface was similar in width to a regular letter-sized sheet of paper. The tablet was positioned in front of the children on a tabletop. The pen's construction is described in detail in Chau, Ji, Tam and Schwellnus (2006). The pen barrel was 0.43 inches (11 mm) in diameter, comparable to that of a primary school pencil. The high friction tip of the pen simulated the pencil-on-paper writing experience. TekScan paper-thin sensors (Model 9811) were adhered to the circumference of the barrel to capture the grip force. The sensor strips were replaced six times throughout data collection sessions due to wear and tear. Recordings of the axial and the grip forces were synchronized and stored on a laptop computer. The sampling periods for axial and grip forces were 7 and 4 milliseconds, respectively. The axial data were linearly interpolated to match the sampling period of the grip data prior to analysis.

4.3.3. Handwriting Assessment

The Children's Handwriting Evaluation Scale (CHES) was used (Phelps, J. Stempel L., 1987). The CHES has both a manuscript (CHES-M for Grades 1 and 2) and a cursive version (CHES for Grades 3 and beyond). Students copy a standard text that is two sentences long in the manuscript version and five sentences long in the cursive version. Both versions have scoring criteria to evaluate handwriting speed and legibility. The psychometric properties of the CHES-M and the CHES are excellent (intra-rater reliability 0.82 and inter-rater reliability 0.95) (Phelps & Stemple). There is no published validity or test-retest data available for the CHES. The CHES can be administered in two minutes and is commonly used to assess the speed and quality of

handwriting. Either the quality or the speed score or both can be used to identify students with handwriting difficulties or dysgraphia.

Cursive writing is expected in children who have reached Grade four in North America (Dennis & Swinth, 2001; Graham et al., 1998); however, all the children in the study chose to write in manuscript. This necessitated a hybrid assessment. The children were old enough to copy the longer passage of the CHES, but due to their use of manuscript, the CHES-M quality criteria were applied. The quality score in the CHES-M is based on ten criteria, each worth ten points, resulting in a total score of 100, with 10-point increments. A score of 80-100 indicates good legibility, a score of 50-70 is satisfactory, and a score of 40 or below is poor and remediation is recommended. Given that the age of the current sample exceeded the age range of the normative data, the legibility scores were plotted and the 15th percentile was selected as the cutoff (Graham, Struck, Santoro, & Berninger, 2006); therefore, children who scored 30 or below were identified as dysgraphic. The CHES has twice as many words as the CHES-M and therefore has more chance of errors, so the lower score cut off is justified. Writing speed was estimated in letters per minute (LPM). Neither the rate norms for the CHES-M or CHES could be used because the age and writing format criteria were not met. The children were thus identified as dysgraphic based solely on their quality scores.

4.3.4. Protocol

The participants were assessed in a quiet room within their own school, during school hours. The children sat on a Stokke height adjustable chair, facing a regular school table. A digital camcorder recorded a sagittal view of the child's pencil grasp and the position of the trunk. The chair was initially positioned to support the children's feet to allow for the recommended 90 degree sitting posture (Parush, Levanon-Erez, & Weintraub, 1998); however, posture was recorded but not controlled during the study, allowing the children to assume their own comfortable writing positions. The primary author, who is an experienced occupational therapist, conducted all the assessments. All children completed the CHES twice, once before a 10-minute copy task (CHES 1) and once after (CHES 2).

To familiarize the children with writing on a tablet, they practiced creative writing of one or two sentences on the tablet for one minute before performing the CHES. The children then copied as much of a story as possible for ten minutes. The story was selected from a literacy text for Grade four students provided by one of the participating teachers. The primary author observed the pencil grasp patterns during the assessment. Each pencil grasp was identified as one of the four grasp patterns in Figure 4.1. If a grasp pattern differed from one of the four mature grasp patterns, it was described in terms of number and positioning of digits on the pencil barrel and labeled as “other”. Three children’s pencil grasps were identified as other. The primary author also recorded whether or not the children switched grasp patterns during the assessment. A second experienced rater completed grasp pattern categorization for a quarter of the sample and the same second rater scored ten percent of the sample for quality.

4.3.5. Data handling and analysis

All identifying information was removed from the writing samples and they were scored for speed and quality by the primary author. The writing samples were scored in random order. Intra-rater reliability for the quality of the writing samples was .81. Inter-rater reliability for quality was .93, and for grasp classification assignment was .82. Intra-rater reliability for quality was .81 and for grasp classification was .80.

Data analysis was completed using Matlab version 7.9.0 and Statistical Analysis Software 9.2 programs. Descriptive statistics on grasp distribution were completed. Only the sensors contacted by the fingers were used in the analysis. The sensor data were filtered with a low-pass Butterworth filter with a cutoff frequency of 15Hz to eliminate the noise in the signal. The data from the pen and tablet were then calibrated separately. The following force parameters were derived from the calibrated data: mean grip and mean axial force, coefficient of variation (CV) of grip and axial forces (degree of variability in the grip forces), and change in means and CV’s of both forces from CHES 1 to CHES 2 (delta). Three types of analysis were performed. Using multiple linear regression (MLR) (Armitage, Berry & Matthews, 2008), we examined the relationship between force parameters and each of grasp pattern (DT, DQ, LT and LQ), number

of fingers (tripod versus quadrupod), and position of the thumb (lateral versus dynamic). The MLR model controlled for handedness, gender, teacher and school since these may impact handwriting performance. Since the sensors were replaced several times during the study, we also controlled for the pen.

See Table 1. Sample size requirements for MLR are calculated by multiplying the number of variables by 5 or 10. The sample size for this study was 74, which was sufficient, because even using the higher value of 10, the required samples size would be 60 for the 6 variables included in the model.

4.4. Results

4.4.1. Distribution of grasps

A sample of 120 children participated in the study. Data from twenty-six children were discarded due to technical issues with the sensors. An additional 17 children who switched grasp pattern between a lateral and a dynamic grasp, were also eliminated because they crossed groupings in the analysis. The 3 participants with immature “other” grasp patterns were also removed. The final sample consisted of 74 children (average age 9 years, 11 months), equally divided between boys and girls. The grasp distribution for the sample was: dynamic tripod 22 (30%), dynamic quadrupod 12 (16%), lateral tripod 19 (26%), and lateral quadrupod 21 (28%).

4.4.2. Legibility of writing and speed

The CHES 1 average legibility score was 60 and the average speed of writing was 54.6 LPM. Twenty percent of the sample had CHES legibility scores on the first administration of the assessment that fell below acceptable. This fraction increased to 32% of CHES 2 legibility scores after the 10-minute copy task. The average legibility score on CHES 2 was 40, which was statistically different from that of CHES 1 (t-test, $p < 0.0001$). When the scores for the first and second assessments for individuals were compared, ten children (13.5%) interestingly increased their legibility scores after the 10-minute copy task; however, the remainder of the children’s scores decreased. The writing speeds on the CHES 2 and CHES 1 were not significantly different (t-test, $p = 0.23$, CHES 1 = 54.6 LPM and CHES 2 = 55.43 LPM).

4.4.3. Effect of grasp on force parameters

Neither grasp pattern (DQ, DT, LT, LQ) nor the number of fingers on the pencil (tripod or quadrupod) had a significant effect on the force parameters for CHES 1, CHES 2 or change in force parameters between CHES 1 and CHES 2 (delta) (see Tables 2 and 3). Only thumb position (lateral or dynamic) had a significant relationship with mean grip force, mean axial force, and CV of axial force for CHES 1 (See Table 4). The mean grip force during CHES 1 was significantly higher for the lateral thumb position than for the dynamic thumb position ($F(1, 65) = 6.88$, $p = 0.011$, lateral: 5.62N; dynamic: 4.23N). The same was true for the mean axial forces ($F(1, 65) = 5.51$, lateral: 0.96N; dynamic: 0.65N, $p = 0.022$) and the CV of axial force was significantly different ($F(1, 65) = 6.24$, dynamic: 0.77, lateral: 0.70, $p = 0.015$).

For CHES 2, thumb position had a significant effect only on mean axial force (see Table 4), which differed significantly between the lateral and dynamic grasp patterns ($F(1, 65) = 6.43$, lateral: 1.23N; dynamic: 0.88N; $p = 0.014$).

4.4.4. Effect of grasp on change in mean force from CHES 1 to CHES 2

There were no significant effects of grasp on the change in mean of grip and axial forces from CHES 1 to CHES 2 from any of the analyses. This finding indicates that the effort involved in writing for over 10 minutes affected the grasp patterns equally (see Figures 2, 3 and 4).

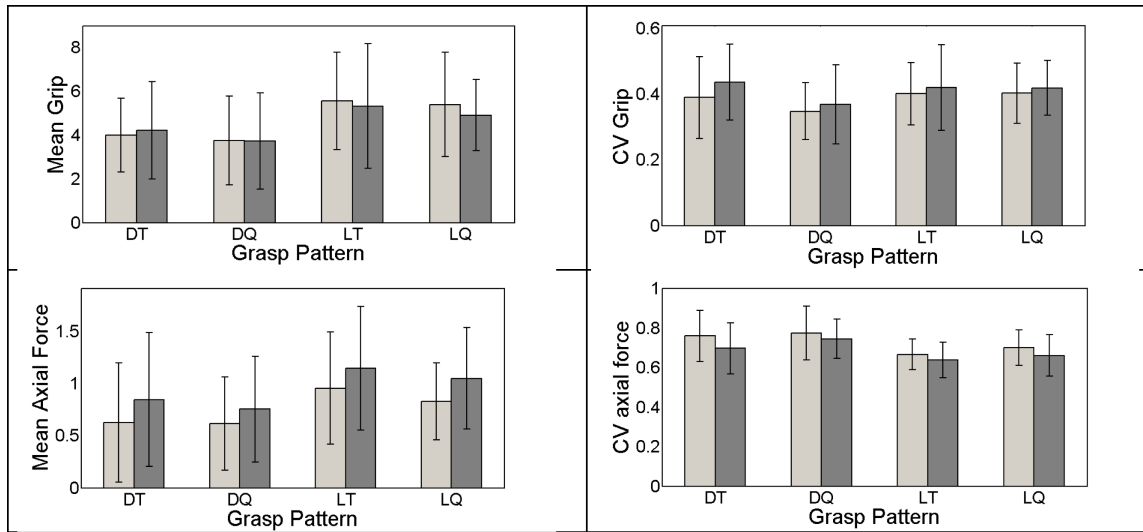


Figure 4-1: The effect of grasp on force (DQ=dynamic quadrupod, DT=dynamic tripod, LT=lateral tripod, LQ=lateral quadrupod, CV=coefficient of variation, light grey = CHES 1; dark grey = CHES 2)

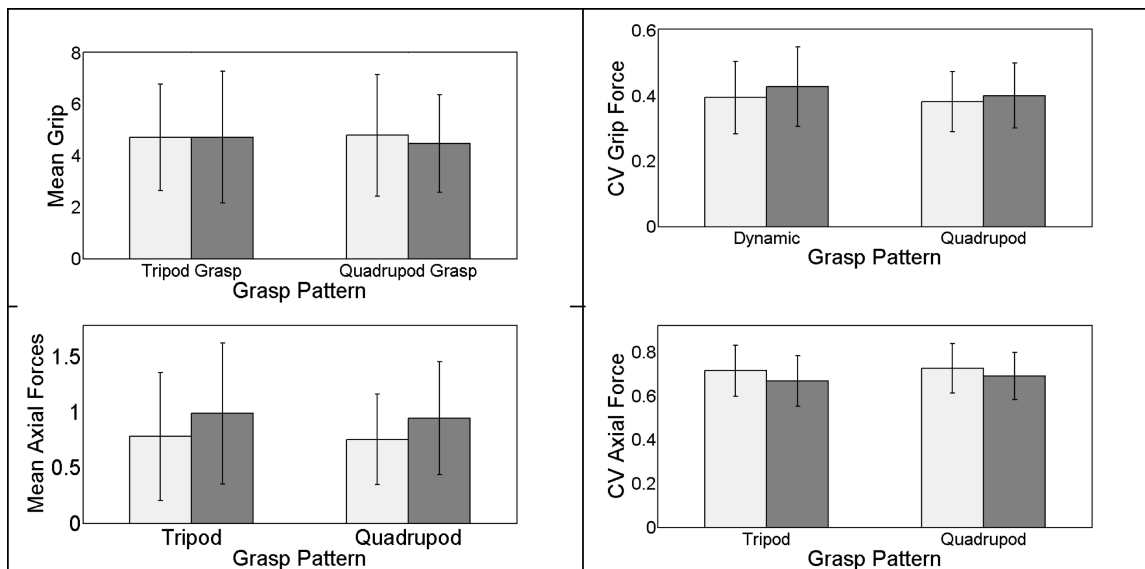


Figure 4-2: The effect of tripod and quadrupod grasps on forces (M=mean, CV=coefficient of variation, light grey = DHES 1, dark grey = CHES 2)

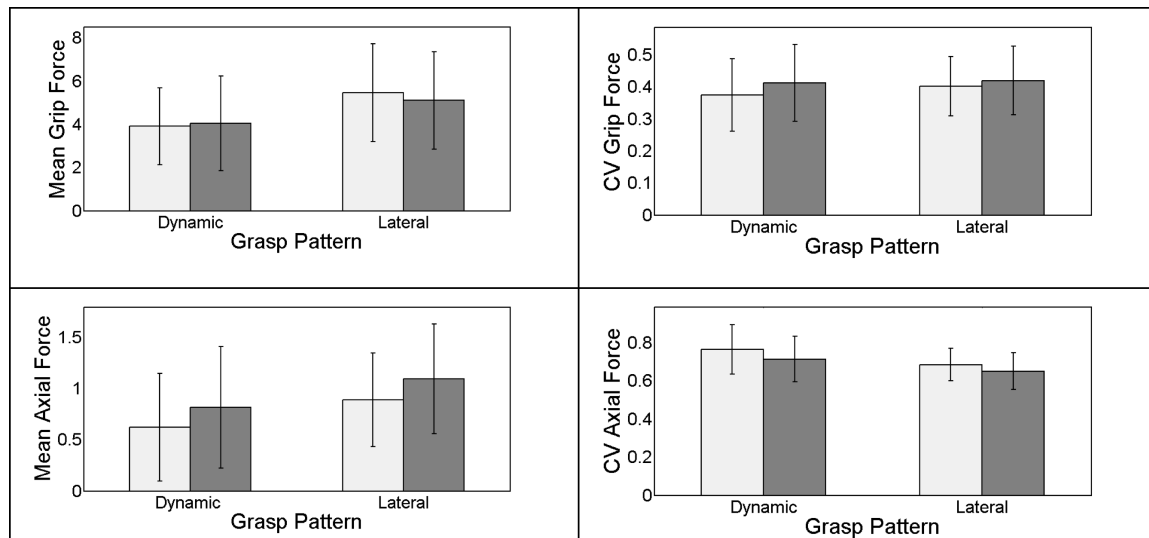


Figure 4-3: The effect of dynamic and lateral grasps on forces (M=mean, CV= coefficient of variation, light grey = DHES 1, dark grey = CHES 2)

4.5. Discussion

4.5.1. Distribution of grasp patterns

Three of the grasp patterns were almost equally prevalent: the dynamic tripod, the lateral tripod and the lateral quadrupod, with the dynamic quadrupod having the lowest prevalence in the sample. Other research has found similar results, (Dennis & Swinth, 2001), which further supports the need to determine whether these grasp patterns can be treated as kinetically equivalent.

4.5.2. Legibility and speed of writing

The legibility scores for CHES 1 indicated that 20% of the sample had dysgraphic writing, which is higher than that found by Overvelde and Hulstijn but is in line with other previous research findings (Graham et al., 1998; Smits-Engelsman et al., 2001). After the ten minute copy task, the percentage of children with dysgraphic writing increased to 32% which indicated that the task overall did fulfill its purpose of increasing the effort of the participants. Interestingly, ten

participants (or 13%) increased their legibility score for CHES 2; four dysgraphic writers actually increased sufficiently to reclassify themselves as proficient. These children may have needed a considerably longer copy task to induce the same amount of effort to impact the quality of their writing to the same degree. An alternate explanation could be that these children found writing on the tablet to be an unfamiliar task and had more difficulty controlling the pencil during CHES 1 but after the copy task, became more familiar with the experience and could control the quality of their writing better. A third explanation is that the instead of classifying children as dysgraphic solely on legibility criteria, rate information is needed to reduce type 1 error.

4.5.3. Grip and Axial forces

The grip and axial forces were not significantly different among the four grasp patterns when they were compared to each other individually or when compared by the number of fingers on the barrel of the pencil. The differences in the mean grip force and the mean and variability of the axial forces of the four grasp patterns were only significant when the grasps were classified by thumb position. A larger amount of force was exerted on the barrel of the pencil when the thumb was adducted and placed over rather than in opposition to the index finger rather. This difference may be due to the need to increase digit force to compensate for the lack of thumb opposition when the tripod or quadrupod is lost (Soechting & Flanders, 2008). That being said, there was no difference in legibility or speed of writing among the four grasp patterns, which corroborates previous results (Koziatsek & Powell, 2003; Schweltnus et al., in press).

The grip forces were not significantly different between any of the grasp patterns in any of the comparisons. This suggests that although the lateral grasps may appear to have a lesser degrees of small movements than the dynamic grasps at the distal finger joints, the variability of the forces is not different for any of the grasp patterns. The variability of the axial force was significantly different for CHES 1 but not for CHES 2. Engel-Yeger & Rosenblum (2010) found that with increased writing speed, which occurred in CHES 2, there was a decrease in distal muscle variability, indicating fixing of the joints to write faster. Consistent with this finding, in the current study, the CV of the grip forces did not change from CHES 1 to CHES 2; however, there was more variability in axial force during CHES 1. It is possible that fatigue may have

decreased the motor coordination and therefore movement coordination, and to compensate for this lack of control, the participants may have decreased the variability of the grip force by fixing the distal joints (Aune, Ingvaldsen, & Ettema, 2008) and potentially writing with greater mean axial pressure. Another possible explanation is that the CHES 1 results may have been transient as the children accommodated to writing on the tablet. This explanation is supported by the results from a 2010 study that found that children use previous knowledge of a handwriting task to improve their performance (Engel-Yeger & Rosenblum, 2010).

4.5.4. Effect of grasp on change in mean force from CHES 1 to CHES 2

Grip and axial forces were not significantly different for grasp pattern from CHES1 to CHES 2, suggesting that the forces involved in the four grasp patterns are equally affected by the extended copy task. The children did write faster on CHES 2, and an increase in speed has been found when writing for longer periods (Dennis & Swinth, 2001; Kushki, Schwellnus, Ilyas & Chau, 2011). When writing faster, children may use more force or vary the axial force more and this previously has had the impact of reducing legibility, however this reduction of legibility was not found in the current study (Engel-Yeger & Rosenblum, 2010; Harris & Rarick, 1957; Harris & Rarick, 1959).

4.6. Conclusions

- The kinetics, speed and legibility of writing were not different among children who used four different types of grasps, after ten minutes of writing.
- This lends further support to the equivalence of the four mature pencil grasps for functional for writing, even after an extended copy task.
- Only when the grasps are grouped according to the thumb position do any significant differences in mean grip and axial forces arise; however, these changes in force did not impact the speed or legibility of the writing.
- Lastly, only the mean axial force was significantly different on CHES 2, so although the lateral grasps may evoke higher axial force, they do not evoke higher grip forces, even after the ten-minute copy task.
- Further research should investigate the static or immature grasps to determine whether or not the forces are impacted by the loss of dynamic movement.

4.7. Limitations

This study recruited a volunteer sample from four schools from middle to upper middle class neighbourhoods of a metropolitan city, and thus may not be representative of the general population. The teaching curriculum is standardized for the school board, but there is room for interpretation in the guidelines for written communication so it is not known to what extent children had been previously exposed to instruction in manuscript and/or cursive writing. The final sample was modest in size. The data of 26 students was lost due to technical issues, and we eliminated a further 20 students due to conflicting thumb positions and the use of non-traditional grasp patterns. The students all used manuscript writing as opposed to cursive, which would have been age appropriate, and this altered the scoring cut-offs for legibility and rendered the speed data usable only as raw scores. Writing on the tablet may have been unfamiliar to participants; however, the initial practice time and the proliferation of pen-enabled gaming devices would have reduced the novelty of tablet-based writing. The 10-minute copy task may not have been sufficient to fatigue all participants, however, it was successful in altering perceived effort scores and was the maximum permissible classroom withdrawal time.

4.8. Acknowledgements

We would like to thank Dr. A. Dupuis and S. Klejman for their assistance with the statistical analysis as well as the staff and students and parents who took part in the study. The project was funded by: the Home Care Research Doctoral Training Award, National Grants Program, SickKids Foundation, Canada Research Chairs Program, the Natural Sciences and Engineering Research Council of Canada and the Graduate Department of Rehabilitation Science, University of Toronto and Children's Rehabilitation Research Network.

Chapter 5

Summary and Contributions

5. Summary and Contributions

5.1. Introduction

A study was conducted to examine the functionality of pencil grasp patterns with respect to speed and legibility of handwriting. The three objectives of the study were: (1) determine the impact of pencil grasps on the speed and legibility of written output of children in Grade 4; (2) determine the impact of a prolonged writing task on the speed and legibility of written output achieved with different pencil grasp patterns, and (3) compare the grip and axial forces of four common pencil grasp patterns and whether they change after a fatigue-inducing task. Presented in this discussion is a summary of the findings, study limitations and clinical implications. Recommendations for future research are suggested throughout the summary section.

5.2. Summary of findings

5.2.1. Pencil grasp pattern and speed and legibility

There was no relationship between pencil grasp pattern and handwriting speed or legibility, corroborating previous reports in children (Dennis & Swinth, 2001; Koziatek & Powell, 2003; Sassoon et al., 1986; Ziviani & Elkins, 1986), and adults (Summers & Catarro, 2003). This study did find lower levels of prevalence for the dynamic tripod grasp. While previous research studies have reported prevalences of 67% (Summers & Catarro), 50% (Dennis & Swinth) and 33% (Koziatek & Powell), the current study found the prevalence of the dynamic tripod to be 23%, only one percent higher than that of the lateral quadrupod grasp. It is possible that with the lowered emphasis on writing in the school system (Graham et al, 2008), that there is also less emphasis encouraging the use of specific pencil grasp patterns, or because these children were not specifically identified as having handwriting difficulties, they may have been allowed to continue the use of their chosen pencil grasp pattern.

There was support for encouraging students to use one of the four mature pencil grasp patterns; while there were proficient and dysgraphic writers in each grasp category, only the three participants who used a non-traditional grasp pattern, termed “Other”, were all dysgraphic writers. The positioning of the digits in these three grasps precluded fine distal movements of the fingers and therefore, the movement required to form the letters came from the wrist. As such, these three grasps were static in nature, or immature grasps. These three children had writing that was rated in the dysgraphic group based on the scores for legibility, and two had writing speeds lower than the average speed of the entire group. Further investigation of writing speed and legibility differences between mature and dynamic versus immature and static grasp patterns is warranted as this sample was too small for in depth statistical analysis.

The average printing speed over all participants was 38.5 letters per minute, which was higher than those published for Grade 4 children writing in cursive by Phelps and Stemple, (1985) at 36.9 letters per minute and Koziatsek and Powell (2003) at 32 letters per minute, but slower than those published by Graham et al., (1998) where children using a mixture of manuscript and cursive wrote the fastest, at 63.3 letters per minute. The children in the current study used only manuscript rather than cursive or a mixture and this may have impacted the speeds recorded. We also found that the time of year of assessment affected handwriting speed. Specifically, students assessed in the spring (concluding Grade 4) wrote faster than the students assessed in the fall (starting Grade 4). The respective speeds were 55 LPM (spring) and 45 LPM (fall). This is consistent with results from Graham et al., who found that the speed of writing continues to increase through primary school (Graham et al., 1998).

Unfortunately, the Handwriting Proficiency Screening Questionnaire, or HPSQ results were not highly correlated with the CHES results. The language in the HPSQ may have been an issue as some of the questions included double negatives, which may not have been interpreted correctly by the teachers. It is possible that the cut-off used to determine dysgraphia may need to be higher; because the suggested cut off score of 14 led to a very high percentage of dysgraphic students. Following the guidelines from Graham et al., (2008) to achieve 85% of the students being designated as proficient, a cut-off score of 20 and higher was needed for a dysgraphic classification. Further research on the use of this tool with English speaking teachers may be warranted.

This study adds to the literature supporting the inclusion of more than one functional grasp pattern for writing as there were no differences in speed or legibility between the four mature grasp patterns in the study. Although pencil grasp may be worth documenting, these results suggest that occupational therapists and educators should reconsider whether or not it is appropriate to try to alter a child's grasp pattern, if the student is already using one of the four mature common grasp patterns.

5.2.2. Fatigue and pencil grasp patterns

In this study, we used a 10-minute copy task to induce fatigue. The 10-minute copy task did appear to serve its purpose; the Pictorial Children's Effort Rating Table or PCERT scores for perceived effort increased after the 10-minute copy task. Pencil grasp pattern did not significantly affect perceived effort. The fact that there was no difference in the rating of perceived effort among children using different pencil grasps may be due to the similarity of the muscles involved in the different grasp patterns. These muscles were likely affected by the long copy task, regardless of pencil grasp. The legibility of the writing samples decreased after the 10-minute writing task. The decrease in legibility occurred across the entire sample, with no significant differences between the different grasp patterns. The speed increased slightly across the entire sample as well, with no differences noted for the different grasp patterns. The decrease in legibility and increase in writing speed has been proposed as compensation for the impact of fatigue on the muscle function of the hand and arm, with individuals writing faster as time progresses (Kushki et al., 2011; Parush et al., 1998; Udo et al., 2000). This increase in writing speed may also be a manifestation of the speed-accuracy tradeoff (Graham et al., 1998; Weintraub & Graham, 1998).

Overall, it appears that the four pencil grasp patterns were not differently affected by the 10-minute writing task. The dynamic tripod grasp with the well-coordinated movements from the interphalangeal joints and those of the hand and forearm did not show an advantage over the other three grasp patterns commonly observed, including the dynamic quadrupod, lateral tripod and lateral quadrupod. The practice of recommending the dynamic tripod pencil grasp in isolation is questionable based on these results. It may be that therapists' precious clinical time

may be better spent looking beyond the pencil grasp (Peterson & Nelson, 2003, Olsen, 2007) and targeting remediation to improve writing quality or speed rather than altering pencil grasp.

5.2.3. Axial and grip forces of pencil grasp patterns

Statistically significant differences in mean grip force and mean and variability of axial forces of the four grasp patterns only occurred when the grasps were classified by thumb position. There was a larger amount of force exerted on the barrel of the pencil in the lateral grasps, which had the thumb in adduction position (placed over the index finger) rather than in the dynamic grasps when the thumb was in opposition (placed against the barrel of the pencil). An increase in grip force may be necessary to accommodate for the lack of opposition provided by the thumb when it is placed on the barrel of the pencil, with the other two or three fingers having to grip with more force to stabilize the pencil when the tripod or quadrupod is lost (Soechting & Flanders, 2008). Regardless of this increase in grip force, there was no difference in legibility or speed of writing for the four grasp patterns, which replicates previous results (Koziatsek & Powell, 2003; Schwellnus et al., 2011).

Both the mean and the variability of the axial forces were different between the lateral and dynamic thumb position during the first administration of the CHES (CHES 1), however only the mean axial force was significantly different between the lateral and dynamic thumb positions on the second administration of the CHES (CHES 2). It should be noted that the differences in mean or variability of axial force from CHES 1 to CHES 2 were not statistically significant. The mean axial force increased for both the lateral and dynamic grasp patterns but remained higher for the lateral patterns.

The results of the study suggest that the effect of grasp on change (delta) in force parameters from CHES 1 to CHES 2 was not significantly different, suggesting that the force parameters involved in the four grasp patterns are equally affected by the extended copy task. The children did write faster on CHES 2, (CHES1 54.6 LPM and CHES2 55.43 LPM) and an increase in speed has been found when writing for longer periods (Dennis & Swinth, 2001, Kushki et al. 2011). When writing faster, children may use more or vary the axial force more and this previously has had the impact of reducing legibility, however this was not found in the current study (Harris & Rarick, 1957; Harris & Rarick, 1959). The larger amount of force exerted on the

barrel of the pencil with the thumb in adduction rather than in opposition may be an accommodation for the lack of opposition provided by the thumb.

The variability of the grip forces was not significantly different between any of the grasp patterns in any of the comparisons. This suggests that, although the grasps may appear from observation to have different amounts of movement, the variability of the forces was not different for any of the grasp patterns. This would support the relabeling of the lateral tripod and quadrupod grasps with a “dynamic” modifier to further distinguish them from static grasp patterns.

The variability of the axial force was significantly different between the lateral and dynamic thumb positions for CHES 1 but not for CHES 2. With increased writing speed, muscle variability decreases; faster writing is performed with fixed joints (Engel-Yeger & Rosenblum, 2010). Consistent with this finding, in the current study the CV of the grip forces did not change from CHES 1 to CHES 2. Fatigue decreased the motor control, so to make up for this loss of control, participants may have fixed the distal joints to decrease the variability of the grip force (Aune, Ingvaldsen, & Ettema, 2008) and potentially writing with greater mean axial pressure. Another possible explanation for the lack of statistical difference in CV of axial force between the lateral and dynamic thumb positions for CHES 2 would be that the CHES 1 results could have been transient as the children accommodated to writing on the tablet. This explanation is supported by the results from a 2010 study that found that children use previous knowledge of a task to improve their performance (Engel-Yeger & Rosenblum, 2010).

5.3. Conclusions

This study contributes to the literature by augmenting the evidence of kinetic and functional equivalence of the dynamic tripod, the dynamic quadrupod, the lateral tripod and the lateral quadrupod pencil grasp patterns. Speed and legibility of writing was not different for any of these four grasp patterns. Regardless of grasp pattern, speed and legibility were similarly affected by a fatigue-inducing condition. In addition, for two of the analyses, that concerning the number of digits on the pencil and the traditional labels for the grasps, the effect of grasp pattern was not statistically different among any of the force parameters. The only significant differences

occurred when the grasps were grouped by thumb position, which included lateral versus dynamic grasps.

5.4. Limitations

This section discusses the limitations of conducting research in a natural setting within a school. To conduct a study in a school setting, the withdrawal time from the classroom needed to be minimized. Although previous research suggested that a 10-minute copy task was sufficient to induce fatigue in children (Parush et al., 1998), a longer task would have ensured that fatigue was more strongly felt by the participants. In addition, the short withdrawal time limited the choices of handwriting assessments to either the CHES or the Minnesota Handwriting Assessment, as both of these tests are completed in about 2 minutes compared to the Evaluation Tool of Children's Handwriting, which takes considerably longer to administer. The equipment had to be portable and easily set up in a number of rooms and settings. This placed restrictions on the size of the tablet, which was slightly smaller than a typical piece of paper. The seating was standardized through the use of a height-adjustable chair to accommodate the variety of table surface heights at the different schools. This limited comparisons of posture as some children used the footplate on the chair and others, due to table height, were able to use the floor. To ensure that the instrumented pen was functioning properly, the sensors were changed six times throughout the study. This complicated the analysis as each pen was uniquely calibrated and this needed to be taken into account with the calculations. A final limitation of the study was that all the children wrote in manuscript, which was not expected given the grade level of the participants. This complicated the grading of the legibility of the samples and allowed only raw score comparisons of the speeds. The published rates for speed for Grade 4 relate to cursive writing and cannot be considered equivalent to rates for manuscript (Graham et al., 1998).

5.5. Clinical relevance

Pencil grasp is a highly charged topic in handwriting clinical practice as evidenced by the numerous pencil grasp devices available through therapy retailers as well as the literature from schools where the “correct” grasp (dynamic tripod) is still the focus of instruction (Benbow, 2002; Case-Smith 2002; Graham, et al., 2008; Rosenblum, Goldstand & Parush, 2006). The

long-standing although not evidence-based, premise that the dynamic tripod grasp is the most functional of the mature pencil grasp patterns still has considerable presence (Graham et al., 2008, Rosenblum et al., 2006). The results of this study help to clarify this situation, finding that speed and legibility of writing were not impacted by any of the four mature pencil grasp patterns, even when a prolonged copy task was performed between the administrations of a standardized handwriting assessment. Further supporting the equivalence of the pencil grasps is the finding that the forces are similar for the four pencil grasps except when grouped by lateral and dynamic thumb positions and then only the mean axial force shows significant differences after the 10-minute copy task. The results of this thesis further support the suggestion that use of any of the four mature pencil grasps under investigation doesn't significantly affect the speed or legibility of written output of Grade 4 children with or without handwriting difficulties.

Children with handwriting difficulties are frequently referred to occupational therapists (Reid et al., 2006), the child's pencil grasp is often one of the first aspects that are noted during assessment (Rigby & Schweltnus 1999; Engel-Yeger & Rosenblum, 2010). The traditional writing grasp, the dynamic tripod, is still thought of as the optimal grasp for handwriting (Graham et al., 2008); however, there are three other pencil grasp patterns that have gained research support as functional options for children, the lateral tripod, the dynamic quadrupod and the lateral quadrupod from this study. The suggestion that a pencil grasp does not matter is not supported, but the suggestion that there is more than one functional pencil grasp has been supported in the literature (Dennis & Swinth, 2001, Koziatsek & Powell, 2003), and finds further support with the results of this study. There are pencil grasp patterns that are static and immature in nature, which biomechanically do not allow the fine dexterous movements necessary for handwriting (Tseng & Cermak, 1993) and should be addressed by therapist; however, a child with handwriting difficulties who is using one of the four mature grasps would benefit from intervention aimed at improving the speed or legibility of the child's writing through an evidence based program (Hoy, Egan, & Feder, 2011), not the alteration of the child's pencil grasp. Further research should be conducted with even longer writing tasks to determine if these results hold for higher grades where the length of writing continues to increase and speed becomes an issue (Connelly, Dockrell, Barnett, 2005).

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