

A COMPARATIVE STUDY OF FOREARM AND HAND MUSCLE USAGE DURING HANDWRITING PRACTICE USING HANDWRITING TOOL

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Abstract

The foundation of education is learning how to write and is considered an essential skill. The early years of education are dedicated to learning how to hold a pencil and how to form letters and words. This research aims to investigate whether there are differences in muscle activity usage between various digital handwriting tools and a standard pencil. We compare the electromyogram of five muscles: upper trapezius (TRAP), biceps brachii (BB), extensor digitorum communis (EDC), flexor digitorum superficialis (FDS), and first dorsal interosseous (FDI) during elementary school's practice of forming letters and words. Five types of (digital) handwriting devices were used. The results showed that using Chromebooks, indicating a trend of increasing in TRAP and BB muscle activities. However, using Chromebook, indicating a trend of reducing in FDI muscle activity. Moreover, when practicing forming letters and words with iPad Pro and Livescribe pens, subjects had the lowest TRAP and BB muscle activity. When using a pencil, it indicated a trend of increasing EDC, FDS and FDI muscle activities. The findings also suggest that a Boogie Board Sync, without line space on the black screen of slate, may create difficulty in controlling their strokes on the surface properly, strokes beautification and their aesthetics, and these may ultimately affect muscle activity. Thus, this study indicated a potential lower energy consumption and lower health risks with the digital handwriting technology. Therefore, for preventing long-term negative effects on fine motor skills development digital handwriting tools may be a suitable interface solution for learning environments.

Keywords: Ergonomic design, human computer interaction, electromyography, digital pen

Introduction

Currently, with the development of tablet computers, so called “electronic handwriting” or “digital inking” technologies are increasingly popular (Park, 2015). Electronic handwriting or digital inking may possibly become a digital writing tool for students in the early years of education (e.g., Mann *et al.*, 2014). The foundation of education is

learning how to write and is considered an essential skill. The early years of education are dedicated to learning how to hold a pencil and how to form letters and words (Mann *et al.*, 2014; Wollscheid *et al.*, 2016). In the learning environment, previous research results have indicated that handwriting results in better memory retention than typing;

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additionally, performance in the recognition task is significantly better in the handwriting situation than in the typing situation (e.g., Longcamp *et al.*, 2006; Smoker, 2009; James and Atwood, 2009; Kiefer *et al.*, 2015). Related to this, children are reliant on fine motor skills which are the ability to make movements using the small muscles in the hands and wrists while handwriting. In general, children will master fine motor skills between the ages of 6 and 12 (Syafri *et al.*, 2018). However, for kindergarten stage, age between 3 to 5 years, fine motoric has begun to develop, such as building high towers with bricks toys (James and Engelhardt, 2012), children may start developing small muscles using their non-dominant hand to stabilize objects like paper when playing and drawing (Markovic and Kopas-Vukasinovic, 2012). At this age, the curriculum is designed for developmental psychology which focuses on the physical, mental, social, intellectual and emotional development of children, so high-quality preschools are play-based, such as using clay or dough, climbing, sliding, playing in sand, waterplay, or even play fighting, rather than attempting to provide early formal instruction in academic subjects (Castles *et al.*, 2013; Gray, 2016). For elementary students, age between 6 to 12 years, curriculums are typically designed to provide students with fundamental skills in reading, writing, and mathematics and to establish a solid foundation for learning (Gray *et al.*, 2016), so elementary education is dedicated to develop the coordination of small muscles in the hands and wrists in optimal conditions for literacy training by using activities that employ the use of fine motor skills such as forming letters correctly and learning to write neatly within the lines (James and Engelhardt, 2012; Mann *et al.*, 2014). In fact, while young children should have the opportunity to develop small muscles, previous research results have indicated that handwriting instruments can affect users' risks for developing injury and health risks from working conditions, as well as increasing arm/shoulder muscle fatigue, and hand fatigue, especially during long sessions (Ravindra *et al.*, 2009; Kim *et al.*, 2014). Moreover, previous research results only indicated that different types of digital writing tools (e.g., size, weight, and thickness of pen, feel of the pen on the digital surface) influence children's handwriting quality and experience (e.g., Mann *et al.*, 2014). Two key factors in design, namely positioning of grasp point and balanced distribution of grasp forces among fingers, are found to have relevance to children's grasp development (e.g., Liu *et al.*, 2015). Furthermore, when introducing tablet computers into the classroom, it was acknowledged that tablet

computers have unique features that could promote student-centered learning environments, especially for younger people (Batchelor and Olakanmi, 2015), but the results for young children are still not clear (Mann *et al.*, 2014). Currently, a new generation of tablet computers with a built-in digital pen become widely available. Regarding to the use of tablet computers in education, this provides a new opportunity of using digital pens included in such devices to enhance development of handwriting and related fine motor skill. However, previous results are not sufficient to provide knowledge and guideline to enhance handwriting practice among young children. Therefore, previous results are still the subject of discussion about digital writing devices' suitability to enhance learning handwriting among young children who are still in the small muscle development stages.

To enhance learning handwriting among young children, we should address the need for better understanding of how digital pen affects handwriting and fine motor skill development. An important question in this new generation during practicing how to form letters and words is whether there are differences in muscle activity usage between various digital handwriting tools and a standard pencil. Thus, it is important to understand the use of various digital handwriting tools that may affect users' risks for developing injury and health risks from working conditions. In this research we intend to empirically answer research questions, and to predict, over a short experimental period, the tendency of a user's risk for developing health problems from long-term use of IT instruments for handwriting practice. Muscle activity usage disparity found by collecting EMG data is a predictor and helps explain the appropriate method for young children in hand development and fine motor skills development. In this work we compared the electromyogram of five muscles: upper trapezius (TRAP), biceps brachii (BB), extensor digitorum communis (EDC), flexor digitorum superficialis (FDS), and first dorsal interosseous (FDI) during young children's practice of forming letters and words using five types of (digital) handwriting device: pencil and paper, Boogie Board Sync, Apple iPad Pro, Livescribe Pen and Chromebooks. Unlike iPad Pro, not all Chromebook machines are equipped with a stylus. Our Chromebook machine is a "Samsung Chromebook Plus", which can represent a device equipped with a stylus based on electromagnetic induction technology, as commercialized by Wacom (Wacom, 2021). On the other hand, iPad Pro is based on a capacitive touch screen technology (Statt, 2015).

Materials and Methods

Subjects

Forty-five elementary students at Biboonbompen Demonstrate School, Thailand, (27 males and 18 females), aged between 8-10 years, participated in this study. Participates were recruited to take part in the study by personal contract. 42 subjects were right hand dominant, and all subjects met the criteria, based on their experience of handwriting with no history of upper extremity musculoskeletal disorders or pain, discomfort, trauma or sequelae related to the upper limbs. This experimental protocol was approved by the University's Human Subjects Committee (144/2562) and each subject signed an informed consent prior to their participation in the study (Table 1).

Table 1. Basic data of the participants

N = 45	Classification
Gender	27 males, 18 females
Dominant side	42 Right hand, 3 Left hand
Age (years) [mean (SD; range)]	9.11 (0.804; 8-10)

Experimental Design

Each of the participants is cited at a different time to participate in the experiment. Before evaluating the various handwriting devices, the subjects could familiarize themselves with different handwriting devices including 1. Pencil and paper, 2. Apple iPad Pro, 3. Boogie Board Sync, 4. Livescribe Pen and Paper and 5. Chromebook. Moreover, the seat and work surface were adjusted to match each subject's anthropometry along ANSI/HFES standards (Human Factors and Ergonomics Society, 2007). Over the course of 5 days, each participant was given different versions of the handwriting devices and one short different writing exercise that required the participants to complete a letter word containing only text. Then students completed short handwriting exercises within 5 min (300s) for each different (digital) handwriting device. Each exercise was followed by completing a questionnaire. Finally, during an interview we asked participants to describe their experience with the (digital) handwriting devices and asked them to compare their experience with all (digital) handwriting devices and their preferences. During the handwriting sessions, writing accuracy and speed were recorded by screen recorder software. The order of the input devices was randomized and counterbalanced to minimize any potential

confusion due to the input device testing order (Gerard *et al.*, 2002; Linderman *et al.*, 2009; Pereira *et al.*, 2013). The systematic variation of the order of the input device conditions in a study can enhance the study's interval validity. The procedure allows researchers to control the effects of nuisance variables in design where the same students are repeatedly subjected to treatments (e.g., repeated-measures design) (Kim *et al.*, 2014). More importantly, these prevent the effects of former treatments from spilling over onto later ones as well as helping to balance out the effects of treatment sequence on the result (Bhandari, 2021).

Equipment and Material

Electromyography

The Surface Telemetry EMG version BTS Free EMG300 wireless (BTS Bioengineering Corp.), which is a 16-channel system, with a mode rejection of 126 dB was used to collect the surface EMG (sEMG) signals, conditioned with a digital band-pass filter between 10Hz-350Hz. EMG signals were recorded using digital data at a sample rate of 1,000 Hz. Disposable Ag/AgCl surface electrodes with an 8 mm diameter pick up area (Ambu Blue Sensor P, REF: P-00-S/50) were placed with a 20-mm inter-electrode spacing over the five muscles.

Handwriting Material

In the repeated-measures laboratory experiment, participants performed writing exercises for five-minute sessions on each of five handwriting device conditions including 1. Pencil and paper, 2. Apple iPad Pro, 3. Boogie Board Sync, 4. Livescribe Pen and Paper and 5. Chromebook (Figure 1).

The subject wrote on foolscap folio, with line spacing of 8 mm and paper gramature of 56 g/m 2(g), using a pencil, with a standard, hexagonal, is cut to a hexagonal height of 1/4-inch (6 mm), but the outer diameter is slightly larger (about 9/32-inch (7 mm)).

The subject wrote on A4 size lined dot paper with line spacing of 7 mm using Livescribe pen, a medium ballpoint blue ink with 2.35 mm diameter, a circle barrel with a length of 162.0 mm, a width 14.9 mm and its weight was 34 grams.

The digital handwriting technology characteristics included Boogie Board Sync, iPad Pro and Chromebook. Each of the digital handwriting technologies used in the study were chosen to cover a regular characteristic of digital handwriting technologies that are on offer.

We considered the characteristics based on the accuracy, weight, grips, length, shape, tip size, and other functionality such as touch sensitivity, and electronic erasers. Furthermore, due to the fact that the Chromebook with stylus is the smallest writing utensil, it's no bigger than a pretzel stick, it leads to an impact on the legibility of the handwriting (Sinclair and Szabo, 2015). Researchers adapted a stylus with hexagonal grip barrel casing that can make a huge impact on your child's ability to hold a pencil and make steady writing progress, a hexagonal pencil is the most popular, efficient and comfortable writing implement. It's easy to grip and won't roll off the table or on an inclined surface. (Goonetilleke *et al.*, 2009; Tancia Ltd., 2016) (Figure 1(e)).



(a). Pencil and paper



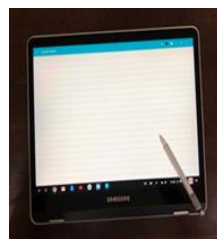
(b). Ipad pro



(c). Boogies Board Sync



(d). Live scribe Pen and paper



(e). Chromebook

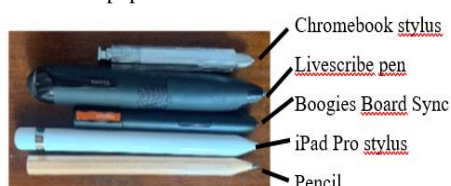


Figure 1. Handwriting devices used in study

Muscle Activity

Muscle activity was recorded from the Trapezius (TRAP), Biceps Brachii (BB), Flexor Digitorum Superficialis (FDS) (Naider-Steinhart and Leurer, 2007; Leonard *et al.*, 2010; Almeida *et al.*, 2013; Kim *et al.*, 2014), and the Extensor Digitorum Communis (EDC) muscle. The TRAP, BB and FDS muscle were selected for their main functions to stabilize and move the upper arm during fine dexterity activities such as handwriting (Almeida *et al.*, 2013). The EDC muscles were selected for their major role in extending the phalanges, then the wrist, and the elbow. The EDC tends to separate the fingers as it extends them (Kim *et al.*, 2014). Moreover, the first dorsal interosseous site (FDI) was selected for their main functions of an important role in fine movements of the hand, being responsible for both index flexion and abduction (Botelho *et al.*, 2017).

Electrode Placement

The location of muscles was identified through palpation during voluntary contraction (Basmajian and Luca, 1985; Perotto and Delagi, 2005). The active electrodes for the TRAP muscle were placed 2 cm lateral to the halfway point between C7 and the right acromium process (Jensen *et al.*, 1993) (Figure 2(a)). The BB was identified by asking the subject to flex their forearm in the supinated position and then the palpate muscle mass in the anterior aspect of the arm emerges (Criswell, 2011) (Figure 2(b)). The EDC was identified by palpating the muscle on the dorsal side of the forearm one third of the way up the forearm and having the subject wiggle their fingers. The electrodes were located where the muscle contractions could be felt (Basmajian and Luca, 1985; Perotto and Delagi, 2005) (Figure 2(c)). Similarly, the FDS was located by touching the muscle on the palmar side one third of the way up the forearm and locating the electrodes where the muscle contractions could be felt (Perotto and Delagi, 2005; Jensen *et al.*, 1993) (Figure 2(d)). The FDI can easily be palpated during the pincher grasp (thumb opposes index finger) (Criswell, 2011) (Figure 2(e)).

Prior to applying the EMG electrodes to the skin, the electrode contact area was prepared by shaving where necessary and then the skin surface was cleaned with Alcohol 70° GL prior to electrode fixation in order to reduce contact impedance. Then, the electrodes were connected to wireless surface sensors and the system communicates with a PC through a WiFi router, which manages 5 electrode channels simultaneously.

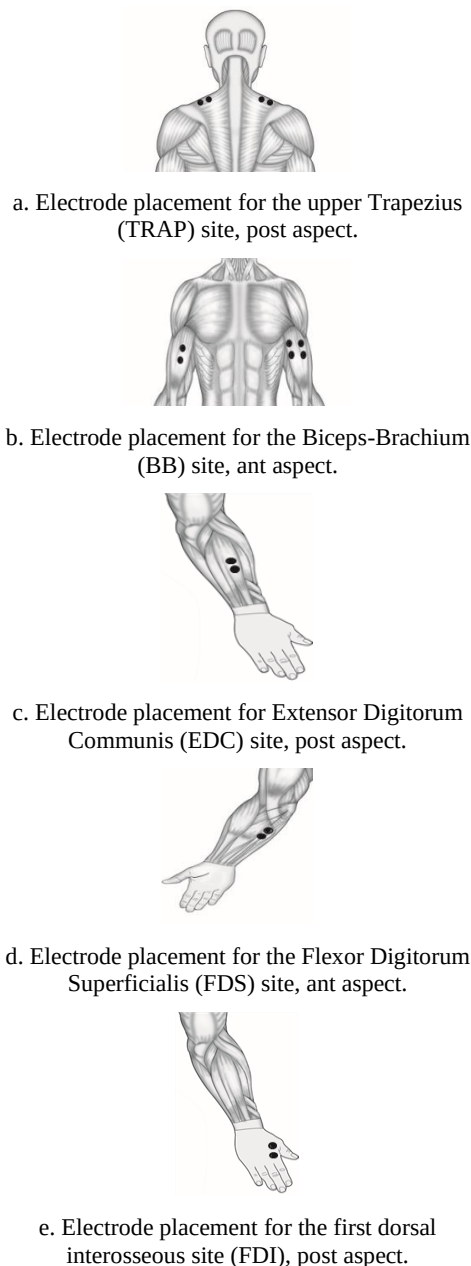


Figure 2. Electrode placement

EMG Data Acquisition and Analysis System

The electrodes were connected wirelessly to the BTS Free EMG300 (BTS Bioengineering Corp.) with a common mode rejection of 126 dB and then they were converted from analog-to-digital (A/D). The raw EMG data was fed into a specific analysis system programmed with EMG-Analyzer software for further analysis. The analysis system used Root Mean Square (RMS) to eliminate the interference of ambient electromagnetic fields (Peter, 2005), and Butterworth high pass filter at 20 Hz was used to apply additional digital filters to minimize the phase

shift phenomenon in the RMS algorithms (Peter, 2005). Moreover, the analysis system was equipped with a band pass in the range of 10-350 Hz filter that were needed to avoid anti-aliasing effects within sampling (Peter, 2005).

The filtered EMG data from the TRAP, BB, EDC, FDS and FDI muscles were normalized relative to Maximum Voluntary Contractions (%MVC) for each muscle (Figure 3), the 10th (static), 50th (median) and 90th (peak) muscle activities were calculated (Jonsson, 1982). To obtain the two MVCs, an isometric contraction was held at the outer-range position, the subjects were instructed to extend their wrists and fingers up against isometric resistance (EDC) and to flex their fingers down against isometric resistance (FDS) with verbal encouragement. To obtain BB MVCs, the subjects were instructed to exert force with the elbow flexor muscles and to minimize the involvement of other muscles (Riley *et al.*, 2008). To obtain TRAP MVCs, the isometric resistance was applied as subjects performed a continuous single shoulder shrug with their arms at their sides and without bending or twisting at the hips/waist (Harms-Ringdahl *et al.*, 1996; Schuldt and Harmsringdahl, 1988). To obtain FDI MVCs, the first dorsal interosseus can readily be seen and felt in vivo during abduction of the index finger against resistance (Criswell, 2011). Each contraction time lasted for three to five seconds (Soderberg and Knutson, 2000). Five MVCs were collected from which the maximum RMS signal over a 1s period was identified and used to normalize the EMG data

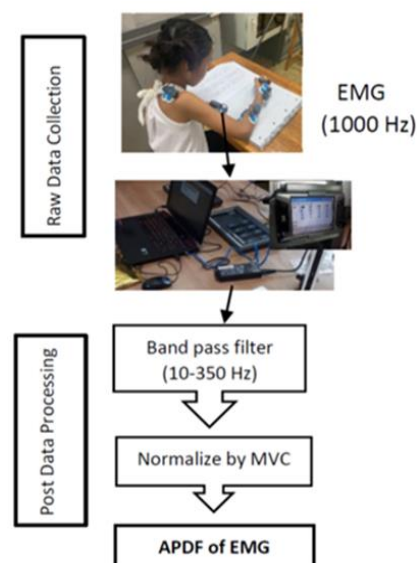


Figure 3. Experimental setup

Data Analysis

In order to reduce variation and condense the colossal data, the section corresponding to the task execution was divided into 5 times periods of electrical activity (EA). The first collection started at the second of 60-s epoch (time window) and the next collection was done every 60 second. An analysis system was calculated EMGs values for every 30-s epoch (Keenan and Cuevas, 2008). Filtered EMGs was normalized by the maximum voluntary contractions (MVC). The data was analyzed with statistical software SPSS for Windows (version 21.0) (SPSS Inc., Chicago, IL, USA). We employed the method of means contrast based on analysis of variance (ANOVA) for the following reasons: (I) the sample followed a normal distribution, (II) the number of groups to be analyzed was greater than two, (Pencil, iPad Pro, Boogie Board Sync, Livescribe, and Chromebook,) ANOVA is an inferential statistic for analyzing the mean difference between muscle activities. This statistic can control Type I errors. In those cases, having a difference between the means, an additional exploration of the difference among means multiple comparisons test, is needed. Any statistical significance was followed-up with a post-hoc Tukey HSD to determine whether there were significant differences between handwriting and typing devices.

Results and Discussions

The results of the EMG analysis indicated variations in muscular behavior during the execution of the practicing to form letters and words at a normal speed as follows.

Upper Trapezius

The results indicated that there were differences in upper trapezius (TRAP) muscle activity between (digital) handwriting devices (Figure 4). The Chromebook had consistently a significantly higher TRAP activities for 10th, 50th, and 90th percentile muscle activity, compared to iPad, Livescribe and pencil ($p < 0.05$). Moreover, the Chromebook had also significantly higher peak muscle activity (90th percentile) compared to the Boogie Board Sync ($p < 0.05$).

Biceps Brachii

The Chromebook had significantly higher biceps brachii (BB) activity for 90th percentile muscle activity, compared to iPad and Livescribe ($p < 0.05$) whereas there was no statistical significance obtained from comparison among

(digital) handwriting devices, especially, for 10th and 50th percentile muscle activity, as illustrated in Figure 5.

Extensor Digitorum Communis

The pencil had higher extensor digitorum communis (EDC) activity for 50th and 90th percentile muscle activity, compared to the iPad ($p < 0.05$) (Figure 6). whereas there were muscle activity differences among (digital) handwriting device for 10th percentile muscle activity (Figure 6).

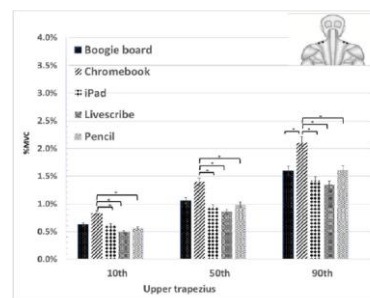


Figure 4. Comparison of 10th 50th, and 90th %tile muscle activity of trapezius. *Statistical significance at $\alpha = 0.05$

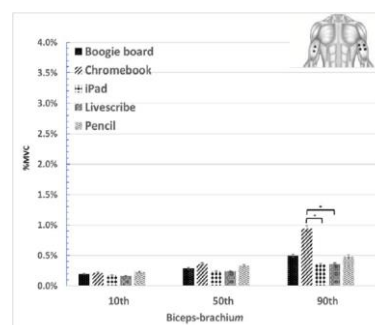


Figure 5. Comparison of 10th 50th, and 90th %tile muscle activity of biceps brachii. *Statistical significance at $\alpha = 0.05$

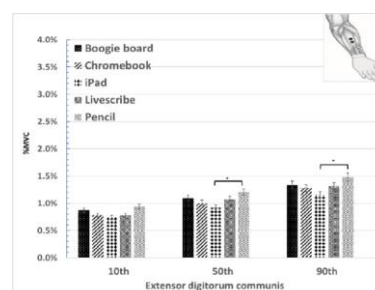


Figure 6. Comparison of 10th 50th, and 90th %tile muscle activity of extensor digitorum communis. *Statistical significance at $\alpha = 0.05$

Flexor Digitorum Superficialis

There were no significant differences in flexor digitorum superficialis (FDS) muscle activities across (digital) handwriting device (Figure 7). However, among (digital) handwriting devices, pencils showed slightly higher muscle activities during the execution of the practice to form letters and words.

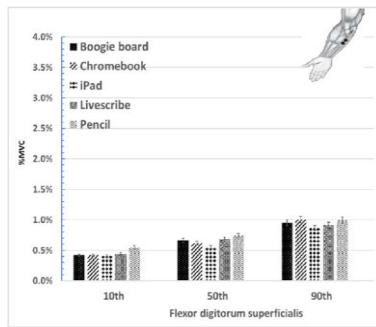


Figure 7. Comparison of 10th 50th, and 90th %tile muscle activity of Flexor digitorum superficialis. *Statistical significance at $\alpha = 0.05$

First Dorsal Interosseus

There were no significant differences in flexor digitorum interosseus (FDI) muscle activities across (digital) handwriting device (Figure 8). Although no statistical significance was obtained, pencils showed higher muscle activities during the execution of the practicing to form letters and words.

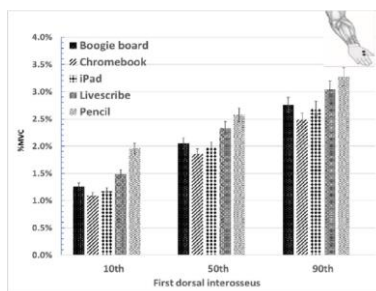


Figure 8. Comparison of 10th 50th, and 90th %tile muscle activity of First dorsal interosseus. *Statistical significance at $\alpha = 0.05$.

Discussions

This present study evaluates whether using (digital) handwriting devices affect muscle activation, the physical risk factors associated with (digital) handwriting device use during practice to form letters and words and the differences with traditional input instruments. This study helps to explain the appropriate methods for young children

in hand development and fine motor skills development. This research results provide evidence on, over a short experimental period, the tendency of users's risk for developing health problems from long-term use of IT instruments for handwriting practice. The EMG results indicated that when using Chromebook participants had a trend of higher TRAP and BB muscle activities. Although, this present study showed that the practice to form letters and words with Chromebooks required consistently higher muscle activity for the TRAP muscle compared to iPad Pro, Livescribe pen, pencil, and the Boogie Board Sync, especially for the 90th percentile muscle activity (Figure 4). Chromebooks only required the higher muscle activity for BB activity and peak muscle activity compared to iPad and Livescribe. There was no muscle activity deference in comparison among (digital) handwriting devices for the 10th and 50th percentile muscle activity (Figure 5). These findings are consistent with (Almeida *et al.* 2013), found that when a subject executed a handwriting task, major activity of both TRAP and BB was observed, indicating the adoption of proximal joint movement such as shoulder elevation and elbow flexion during handwriting tasks. This is likely that higher TRAP muscle activities in Chromebook may be caused by some students concerned about touchscreen zones, they lift their arm all the time during practice to form letters and words (Figure 9). However, many participants expressed their feeling about Chromebook that the "stylus tip felt almost like a real pencil and there was enough friction between the stylus and screen to feel natural."

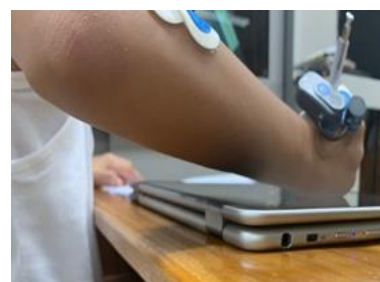


Figure 9. The image show children's writing and posture

According to the observation, stroke beautification and productivity were similar among Boogie Board Sync (Figure 10(a)) and Livescribe pen (Figure 10(b)) respectively. Thus, our analysis of all the descriptive and letter formation shows that higher TRAP and BB muscle activities in Chromebook may because

the difference in adapting movement patterns for individuals. These were thought to be a result of improper handling in modification of their behavior, so they would have a difficult movement and eventually, it may lead to the higher muscle activities. Thus, beyond the reaction to a handwriting tool, especially stylus tip, the mishandling the display may have influenced on their posture and eventually may affect muscle activity.

Additionally, the participants had higher BB activity when using Chromebook (Figure 5). This is likely because the adoption of proximal joint movements, such as shoulder elevation and elbow flexion during the handwriting practice (Almeida *et al.*, 2013), as illustrated in Figure 11. This study finding is consistent with Duarte *et al.* (2017) and found a correlation between the BB muscle activity, speed of the movement, handwriting style and stroke size. This suggests that major function of BB muscle as a stabilizer and mover of the upper arm is kept during handwriting tasks regarding the elbow flexion and extension level (Duarte *et al.*, 2017).

When using Chromebooks and iPad Pro, participants had consistently lower EDC (Figure 6),

and FDI (Figure 8) activities for the 10th, 50th, and 90th percentile muscle activities. While Chromebooks had a higher EDC muscle activity than iPad Pro, the iPad Pro had a higher FDI muscle activity than Chromebooks. However, there were no muscle activity differences between the Chromebooks and iPad. This is likely because of both of stylus had pressure sensitivity and low lag (delay) between the stroke and what shows up on screen (Statt, 2015). Moreover, when participants expressed opinion about iPad Pro, they were often described as “cool” “I preferred iPad to other handwriting devices.” Participants had impression and positive handwriting experiences with them. Surprisingly, according to our observation, participants could rest their palm and wrist on the display. Unlike Chromebooks, some participants frequently lifted their arm all the time during the practicing to form letters and words. However, stroke beautification was similar between them, but the iPad Pro (Figure 10(d)) had slightly more productivity than Chromebooks (Figure 10(c)). Thus, our analysis of all the descriptive and letter and words formation shows that lower EDC

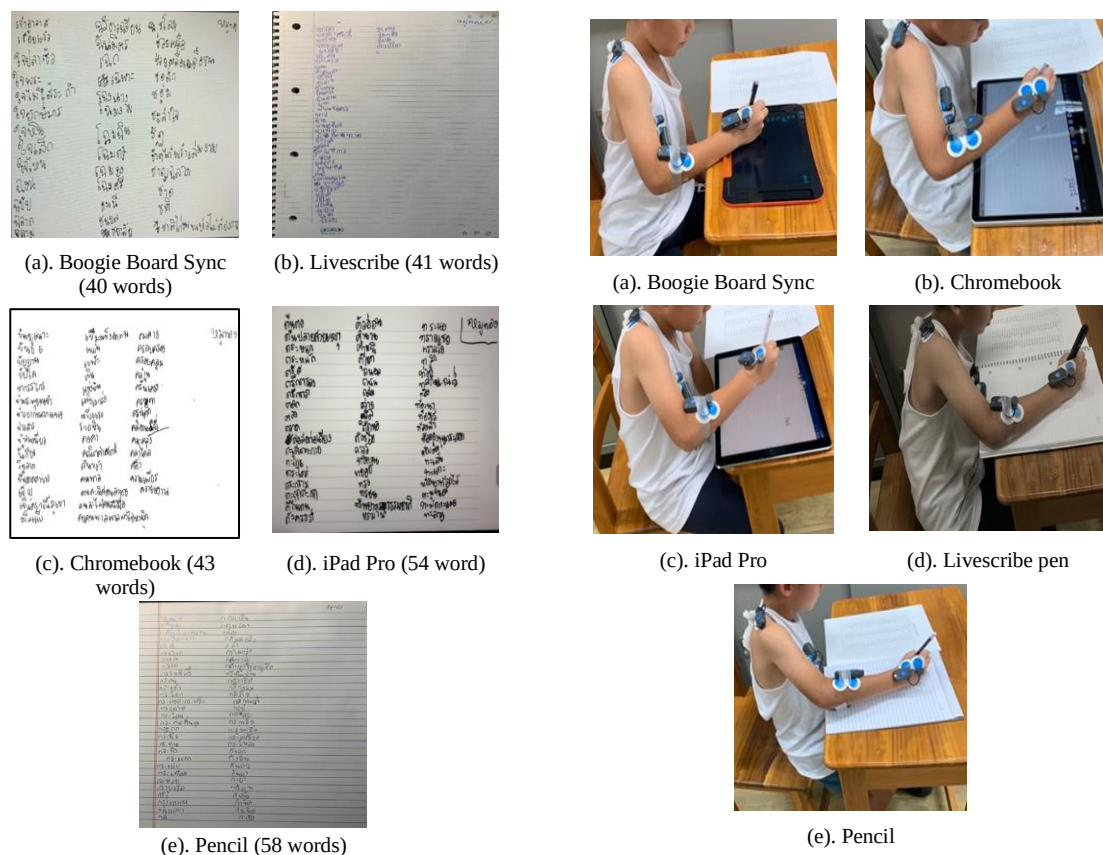


Figure 10. The images were cropped to show the comparisons of stroke beautification and productivity (Participant No. 33)

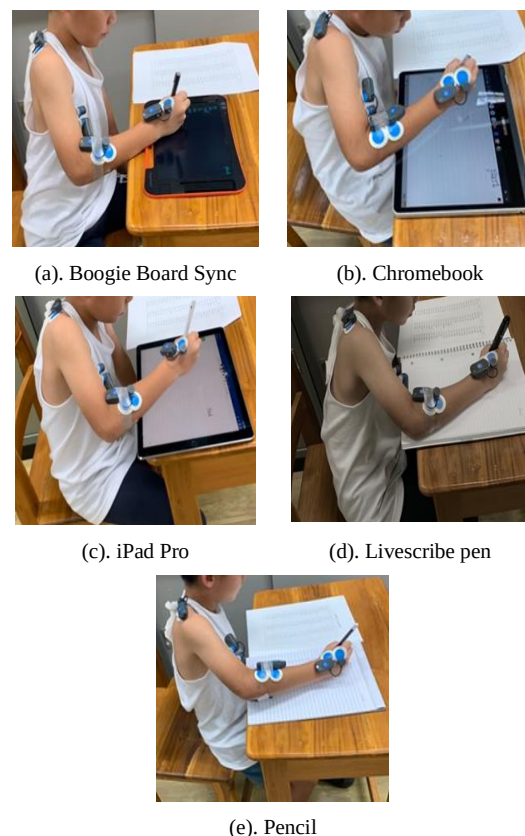


Figure 11. the image show children's writing and the adoption of proximal joint movement. (Participant No. 23)

(Figure 6) and FDI (Figure 8) muscle activities among Chromebooks and iPad Pro may be caused by the mature grasp pattern which is the handwriting activity itself modifying the muscular performance when controlling the stylus on the surface (Mann *et al.*, 2014). This finding is consistent with Duarte *et al.* (2017) and found a correlation between the EDC muscle activity, speed of the movement, handwriting style and stroke size.

Moreover, if we analyzed Chromebook, the results indicated the FDI muscle was consistently higher for the 10th, 50th, and 90th percentile muscle activities compared to other muscle activities (Figure. 12). This is because of the major function of the FDI is the rotation of the index finger slightly at the metacarpophalangeal joint and assist adductor pollicis in thumb adduction (Palastanga and Soames, 2012). The position of the FDI is on the first and second digit, the muscle lies on the lateral side (Okorokova *et al.*, 2015; Valenzuela and Bordoni, 2020). The fact that these small muscles, despite their limited range of motion and together with the interosseous palmar muscles, play key roles in the function of the hand: grip and pinch (O'Rahilly, 2004; Acosta *et al.*, 2020; Valenzuela and Bordoni, 2020) indicated that the thumb is one of the most important entities of the hand. Its versatility in movement compared to the other digits makes the hand the ultimate tool of elite dexterity. Because the thumb is orientated perpendicular to the other digits, its movements are modulated by a diverse set of specific muscles within the hand. Additionally, the adductor pollicis can bring the thumb alongside the palm and index finger. The ability to adduct the thumb is critical for hand dexterity. Pinching and gripping are the two principal movements that necessitate that the adduction processes of the thumb be intact.

When expressing feelings about the stylus (digitizer pen) with casing adapted by researcher, the subjects expressed that "it is fine and easy to grip." "Stylus tip make my handwriting feel authentic." "I never have experience with it before. It is hard to express, but I like it. It is fun." "I think it is different/strange, but it is cool." "I can control to write the correct letters and words." Thus, our analysis of all the descriptive indicate that beyond stylus accuracy, precision of strokes, feel of the stylus on the digital surface and the stylus characteristics such as grips and shape (Yu *et al.*, 2011), a comfortable position and rest their palm, wrist or even their arm on the display invoke a stronger connection to one's pinching and gripping a stylus (digitizer pen) because it may affect them in their writing speed, and posture, and there may ultimately affect muscle activity.

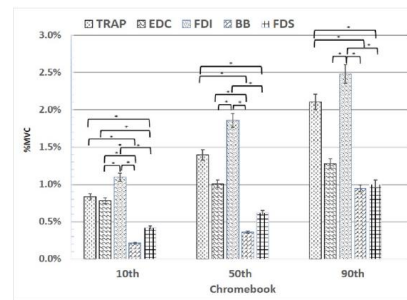


Figure 12. Comparison of the TRAP, EDC, FDI, BB, and FDS muscle activities of Chromebook

According to the observation, when expressing feelings about the Boogies Board Sync, the participants expressed that "It is fun, I like it" However, if we analyze writing size, then we found that it is slightly bigger than other handwriting devices (Figure. 10(a)). This is likely because there was no line space on the black screen of slate, it may create the difficulty to control their strokes on the surface properly, stroke beautification and their aesthetics. Thus, it is indicated that beyond line color of stylus, the black screen of slate with line space invokes a stronger connection to one's writing because it forced them to alter their writing size and variety of pressures, and these may ultimately affect muscle activity (Annett *et al.*, 2014).

When using a Livescribe pen it had consistently significantly lower muscle activity for TRAP when compared to Chromebooks for the 10th, 50th, and 90th percentile muscle activity (Figure 4) and lower BB muscle compared to Chromebook, especially for the 90th percentile muscle activity (Figure 5). These findings are consistent with (Almeida *et al.*, 2013) and found that a pen's muscle activity showed a higher TRAP and BB muscle activity when perform handwriting tasks because of the difference of grasp patterns in which there is an expenditure of different muscle activities (Figures 13(a), 13(b), and 13(c)). Moreover, during interviews, Livescribe pen was described as big, but fun and easy to control. This is likely because Livescribe is similar to ballpoint pen. The pen nib is fluid and smooth and the feed's ink flows smoothly (Goonetilleke *et al.*, 2009). Thus, beyond the grasp pattern, characteristics of pen: the size and weighs, the nib and ink feed are one of the most important components that may affect muscle activity. Thus, design guidelines for pen/pencil interaction using variations of grip postures should/could be identified to suit the type of pen/pencil task such as handwriting, drawing and shading (Matulic *et al.*, 2019).

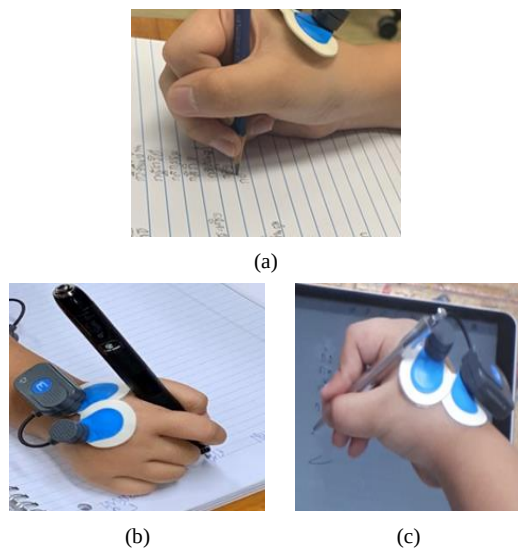


Figure 13. Participant's handwriting samples from pencil (a) Livescribe (b) and Chromebooks (c)

Additionally, the participants had higher EDC activity when using a pencil for 50th and 90th percentile muscle activity, compared to the iPad (Figure 6). According to the observation, the number of words and quality of handwritten output is acceptable for legible handwriting. There are a variety of stroke sizes and the pressure on the nib of the pencil (Figure 10). This is likely because of the writing on paper with pencils is familiar to participants from childhood (Schwellnus, 2012). The proper way to hold a pencil can make a huge impact on handwriting productivity. It can reasonably be assumed that there is the correlation between the EDC muscle activity, speed of the movement, handwriting style and stroke size (Duarte *et al.*, 2017; Zaman and Stegemoller, 2018). Thus, our analysis of all the descriptive and letter formation indicated that beyond handwriting style and stroke size, speed of handwriting could be considered, and these may ultimately affect muscle activity. Thus, when assigning written exercises, teachers should be aware of the proper handwriting exercise between time and the number of words. The length of each handwritten text and number of words is one of the most important factors that may influence on muscle activity.

Although it was not significant, the FDS showed a consistently slightly high muscle activity when using pencil (Figure 7). The findings are consistent with Almeida *et al.* (2013), found that a pen's muscle activity showed a higher FDS muscle activity in individuals when performing handwriting tasks using the static tripod grasp because of the increased use of extrinsic muscles could result in a diminished role of intrinsic hand muscles during

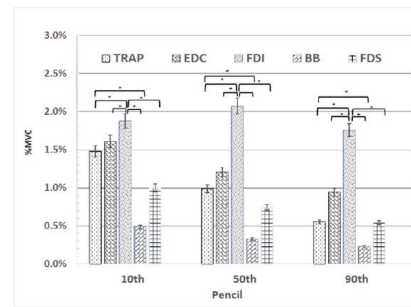


Figure 14. Comparison of the TRAP, EDC, FDI, BB, and FDS muscle activities of pencil

handwriting in this grasp pattern (Ferriell *et al.*, 2000; Edwards *et al.*, 2002; Matulic *et al.*, 2019).

Moreover, if we analyzed the pencil, the activity of the FDI was higher in individuals (Figure 8) as well as there were significant differences in static, median and peak FDI muscle activities compared to other muscle activities ($p < 0.05$) (Figure 14). Obviously, FDI muscle plays an important role in fine movements of the hand, being responsible for both index flexion and abduction and plays key roles in the function of the hand grip and pinch (Valenzuela and Varacallo, 2018; Zaman and Stegemoller, 2018; Botelho *et al.*, 2019). When handwriting on paper with pencils is familiar to participants from childhood (Schwellnus, 2012), and handwriting events were properly handled, many subjects were comfortable, so the speed of writing in individuals may be different (Duarte *et al.*, 2017; Valenzuela and Varacallo, 2018) and eventually it may lead to the difference of muscle activities.

Conclusions

This work provides insight evidence of the difference between handwriting devices in muscle activity. According to the result obtained in the EMG activities, using Chromebooks may be detrimental to muscles after practicing forming letters and words for long sessions. Using Chromebooks, indicating a trend of an increase in TRAP and BB muscle activities. These were thought to be a result of the mishandling the display. However, using Chromebooks indicates a trend of a reduction in FDI muscle activity.

Moreover, when practicing forming letters and words with iPad Pro and Livescribe pen, subjects had the lowest TRAP and BB muscle activity, this may imply that using iPad Pro and Livescribs pen may be an efficient tool for practicing forming letters and words. Moreover, participants had positive experiences with iPad Pro

and felt that these were ideal characteristics for practicing to form letters and words.

When using pencils, it indicated a trend of an increase in EDC, FDS and FDI muscle activities. These were thought to be a result of the pressure on the nib of the pencil and the speed of handwriting. These could be crucial when they accumulate over time.

When using Boogie Board Sync without line space on the black screen of slate it may create the difficulty to control their strokes on the surface properly, strokes beautification and their aesthetics, and these may ultimately affect muscle activity.

Thus, when a task involves practicing forming letters and words, it is more likely that lower energy consumption and lower health risks could be provided by the regular characteristics of digital handwriting technology. Therefore, for preventing long-term negative effects on fine motor skills development digital handwriting tools may be a suitable interface solution for learning environments, and it may prevent the ongoing marginalization of handwriting in writing instruction.

Practical Implications

The research results represent an approach to developing new or innovative methods for using digital handwriting devices. Developers or elementary schools which have students in the early stage of practicing writing skills and fine motor skill development can use a design guideline for digital handwriting practice tools to meet students' needs as follows:

1. If the elementary school uses a digital handwriting tool with a stylus smaller than the size of the #2 pencil group, such as a Chromebook's stylus, schools can provide or apply a pen grip barrel casing to increase the size of the stylus for a better grip, and for the stylus to be as large as the size of the #2 pencil group. It should be a non-slip surface material and have a square shape such as hexagonal, in order to increase the fit of the student's hand as well as it does not slip when placed on an inclined table.

2. According to the observation, Apple pencil (1st generation) has a grip thickness which is similar to the size of the #2 pencil group. Moreover, it has smooth surface material and a circle shape. Similarly, if applying a hexagonal grip barrel casing with a non-slip surface material, this is likely more comfortable for gripping and pinching and will not roll off the table or on an inclined surface. Schools could provide materials

with angular shapes, and the material can be made of cloth or silicone, which can be adjusted according to the shape of each student's hands and fingers. These may reduce the risk of hand injury when hexagonal grip barrel casing provides a good grip, reduce the effort needed to use the Apple pencil effectively, and prevent the device from slipping out of the hand.

3. It is important that the palm rejection feature allows students to rest their palm comfortably on the screen while using the stylus. Similarly, the app's palm rejection is also to help students rest their arm and to reduce concerning touchscreen zones as well as to prevent accidental taps.

4. Additionally, according to the observation, using Boogie Board Sync without line space on the black screen of slate, it may create the difficulty to control their strokes on the surface properly, and strokes beautification. Thus, elementary schools can define lines or dashes with 7-mm or 8-mm line spacing to use as a guide to increase or decrease the font size and control the writing direction.

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