Journal of Electromyography and Kinesiology 25 (2015) 540–547

Contents lists available at ScienceDirect

Journal of Electromyography and Kinesiology

journal homepage: www.elsevier.com/locate/jelekin

Differences in muscle activity patterns and graphical product quality in children copying and tracing activities on horizontal or vertical surfaces

Sigal Portnoy [a,*], Limor Rosenberg [a], Tal Alazraki [a], Esti Elyakim [a], Jason Friedman [b]

[a] Department of Occupational Therapy, Tel Aviv University, Tel Aviv, Israel
[b] Department of Physical Therapy, Tel Aviv University, Tel Aviv, Israel

ARTICLE INFO

Article history:
Received 26 October 2014
Received in revised form 27 January 2015
Accepted 31 January 2015

Keywords:
Motor equivalence
Electromyography
Tablet
Occupational therapy
Muscle fatigue
Motor control

ABSTRACT

The observation that a given task, e.g. producing a signature, looks similar when created by different motor commands and different muscles groups is known as motor equivalence. Relatively little data exists regarding the characteristics of motor equivalence in children. In this study, we compared the level of performance when performing a tracing task and copying figures in two common postures: while sitting at a desk and while standing in front of a wall, among preschool children. In addition, we compared muscle activity patterns in both postures. Specifically, we compared the movements of 35 five- to six-year old children, recording the same movements of copying figures and path tracing on an electronic tablet in both a horizontal orientation, while sitting, and a vertical orientation, while standing. Different muscle activation patterns were observed between the postures, however no significant difference in the performance level was found, providing evidence of motor equivalence at this young age. The study presents a straightforward method of assessing motor equivalence that can be extended to other stages of development as well as motor disorders.

1. Introduction

Motor equivalence is the similarity of movements produced by different sets of motor commands, utilizing different muscle groups (Sporns and Edelman, 1993; Wing, 2000), for example, when signing one's name on a piece of paper or signing it in larger letters, on a blackboard (Merton, 1972). Although different muscles are used to produce the two movements, the graphical product has been found to be similar. This is considered natural in adults; however, motor coordination develops gradually during childhood, as variations in neural and biomechanical structures evolve in the child (Sporns and Edelman, 1993). There is a scarcity of studies that investigate the characteristics of motor equivalence in children. An early study comparing speech-motor equivalence in children, adults and elderly individuals showed that young children and elderly individuals have a similar muscle activity pattern, which differs from that of adults, and which consequently results in alterations of rate and precision of speech (Rastatter et al., 1987). However, the effect of using different muscles to obtain a similar graphical goal in children, e.g. copying a circle, has yet to be investigated. The instruction for children to produce graphic products under different conditions, e.g. using different tools or inclined surfaces, is a common activity in kindergartens and schools. Also, children having difficulties in acquiring graphomotor skills are instructed by occupational therapists to draw on a vertical surface (Amundson, 1992; Judge, 2006), under the unsubstantiated assumption that in this position, the wrist is fixated in a functional drawing position and that shoulder stability is practiced (Benbow, 1995).

Motor equivalence is related to the notion of context-conditioned variability (Turvey et al., 1982). Even when repeating the same task in the same posture, the precise context (e.g. posture, muscle activations, fatigue) is always different between repetitions. These differences mean that the solution for performing the same task also must differ between repetitions. The observation that we produce similar outputs (e.g. when drawing) despite these differences in context implies that the motor programs we use are unlikely to take the form of the muscle contractions necessary to perform a task. Rather, at the muscle and joint level we expect to see significant variability in performance due to these differences in context. In a well-tuned system, we expect that this variability in muscle activations will not, however, lead to significant differences in task performance.

Movements produced in different planes (i.e. horizontally and vertically) are subject to different constraints. For example,

* Corresponding author at: Occupational Therapy Dept., School of Health Professions, Faculty of Medicine, Tel Aviv University, Ramat-Aviv, Tel-Aviv 6997801, Israel. Tel.: +972 3 6405441; fax: +972 3 6409933.
E-mail address: portnoys@post.tau.ac.il (S. Portnoy).

http://dx.doi.org/10.1016/j.jelekin.2015.01.011
1050-6411/

movements in the vertical plane must deal with the effect of gravity which may modify the dynamics of the movement (Atkeson and Hollerbach, 1985). Further, this posture of the hand is related to proximal motor function, i.e. the shoulder and upper arm, rather than distal motor function, i.e., the wrist and fingers. Proximal function has been considered to be a prerequisite for distal function and manipulative hand use (Heriza, 1991), although empirical findings revealed that these two systems might be independent of each other, and relate to different types of control (Naider-Steinhart and Katz-Leurer, 2007). Although clinical experience has implied positive outcomes on grasp when using the upright position of the hand while working on a vertical surface, few empirical studies support this premise. For example, a study with 2-year old infants given a crayon, a pencil, or a marker found that only for the crayon, a more mature grasp was used with an upright easel rather than drawing flat on the table (Yakimishyn and Magill-Evans, 2002), although the level of performance was not evaluated in their study. The lack of studies in this area led us to examine how performance differs between similar tasks performed by children on different surfaces with different body postures.

The objectives of this study were firstly to assess the level of performance of a tracing task and a copying figures task in two common postures, while sitting at a desk and while standing in front of a wall, among preschool children. By comparing muscles activity patterns, we can confirm that the tasks are performed differently in the two postures. Based on our knowledge of motor equivalence, we predicted that the level of performance in both cases would be similar. Despite this, we expected that the proximal muscles will be more activated and fatigued (in longer tasks) while drawing on the vertical surface in a standing position.

2. Methods

2.1. Study design

This was a repeated-measures study, with the inclination of the surface as the independent variable.

2.2. Participants

Thirty five right-hand dominant healthy children (17 boys, 18 girls; mean and SD age of 5.9 ± 0.4 years) participated in this study. Inclusion criteria were healthy five- to six-year old children. Exclusion criteria were any orthopedic or neurologic impairment, visual impairment that could not be corrected with glasses, or ability to understand and follow simple instructions, reported by the parents. All participants were enrolled in fulltime preschool programs and recruited through personal contact and snowball sampling. The study was approved by the Occupational Therapy Department Ethics Committee at the research facility.

2.3. Research tools and protocol

The parents signed an informed consent form and each subject was administered the long form Beery-Buktenica Developmental Test of Visual-Motor Integration (Beery VMI), frequently administered during visual perceptual evaluations (Beery, 1997), during which the subject copies basic shapes. The subjects were divided into two groups, matched according to the percentile ranks of this test (mean and SD: Group 1: 59.6 ± 22.4, group 2: 60.9 ± 22.4; $p = 0.63$). A repeated measure design with counter-balanced order of two conditions was used, with half the participants first tested with the horizontal orientation and then the vertical orientation and the other half tested in the reverse order, to eliminate the effect of learning.

Parts of the Fine Manual Control subtest of the Bruininks-Oseretsky Test of Motor Proficiency (BOT2) (Deitz et al., 2007) were recorded with a digital tablet (Samsung Galaxy Note 10.1 GT-N8010) using an 11.5 cm long stylus provided with the tablet. This tablet has a built-in Wacom digitizer, with a manufacturer specified resolution of 0.01 mm. Specifically, the subjects had to copy four shapes (circle, square, star and wave); and complete two path tracing tasks between two lines (broken or curved paths) – see Fig. 3 for the stimuli. The location of the tip of the stylus on the tablet was recorded at 125 Hz (determined based on the collected data) using custom Android software (available by request from the corresponding author), and was analyzed using custom code (Matlab R2012b, MathWorks, Natick, MA, USA). The raw data were filtered using a 2nd order two-way low-pass Butterworth filter (i.e. effectively a 4th order filter), with a cut-off of 5 Hz. The tablet was set in a wooden frame (Fig. 1), to allow the height of the tablet and frame to be equal. A stand was built to hold the frame in a vertical position, when required and clips were used to secure the tablet when positioned vertically.

A telemetric surface electromyography (sEMG) system (Myon RFTD, Myon AG, CH) with a floating ground and pairs of bipolar Ag/AgCl surface electrodes (Ambu Blue Sensor N-Electrodes, Denmark) was used to measure activity of the upper trapezius (UT), biceps brachii (BB), and extensor carpi radialis (ECR), chosen for their major role during fine dexterity tasks (Linderman et al., 2009; Sporrong et al., 1998). Skin preparation and electrode placement were done according to the sEMG for a non-invasive assessment of muscles (SENIAM) guidelines (Hermens et al., 2000). The electrodes were placed parallel to the general axis of the muscle fibers, with a center-to-center inter-electrode constant distance of 20 mm and remained on the skin throughout the duration of the trial. The system comprises of analogue differential amplifiers and the sEMG signals were amplified no further than 10 cm from the recording site. Data were collected at a sampling rate of 1000 Hz and bandpass filtered (dual-pass 2nd order Butterworth, 10–500 Hz). Data were acquired and analyzed using custom code (LabView V12, National Instruments, Austin, TX, USA). In order to permit amplitude normalization of sEMG data, the subjects performed several maximum isometric voluntary contractions (MVCs) for five seconds for each of the monitored muscles (Burden, 2010; Frost et al., 2012). Recording was initiated following explanation and practice by the subject. The signals were displayed on the computer while acquiring the MVC data in order to provide biofeedback to the subject to elicit a maximal contraction. Further, verbal encouragement was provided by the researcher.

Each subject was asked to copy the four shapes and perform the path tracing tasks twice: once when the tablet was positioned horizontally on the table, during which the subject was seated on a chair, fitted to his or her height. The subject was able to rest the elbow or wrist on the table, but no verbal instruction was provided so that each subject performed the task at his or her on convenience. Each subject repeated the task when the tablet was positioned vertically, and the subject stood in front of it (the center of the tablet was positioned in front of the midline of the subject and the subject was asked to stand at a comfortable distance). The task under each condition, horizontal or vertical, lasted approximately two to three minutes and the subjects were instructed to sit and rest their arm while the tablet was arranged for the following setup.

2.4. Post analysis

2.4.1. Graphical product quality

As the tablet only records when the stylus touches the tablet, movement start and end were determined from the first and last time the stylus touched the tablet. The movement time was

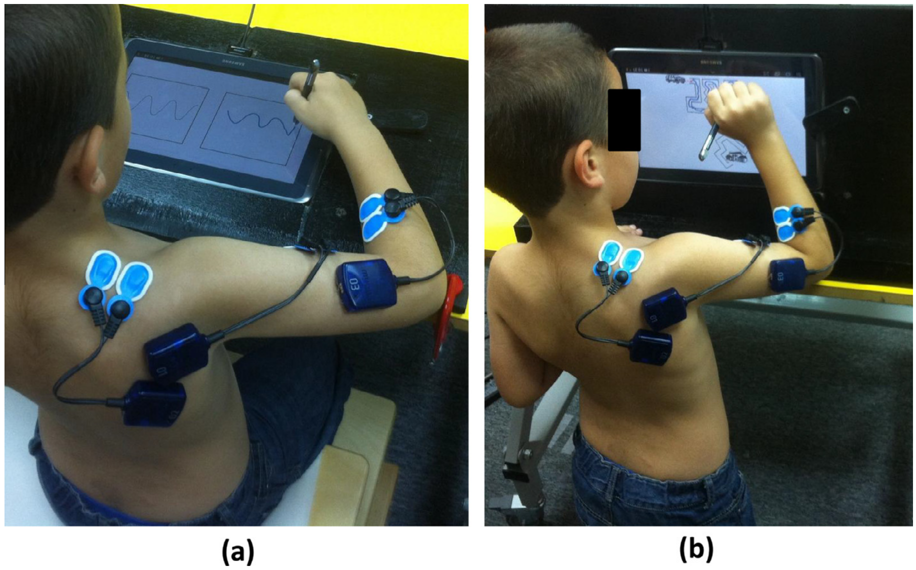


Fig. 1. Experimental setup. The subjects performed the same 6 tasks in the two configurations, with the tablet either oriented (a) horizontally or (b) vertically.

computed as the amount of time the stylus contacted the surface of the tablet. The total number of acceleration zero-crossings in both the x (left–right) and y (front-back or up-down) directions (which correspond to peaks or troughs in the velocity signal) was computed for each drawing, as a measure of the fluency of the drawing. Zero crossings that occurred less than 100 ms after the previous zero crossing were assumed to be spurious and were not included in the count.

For the four copying tasks, the closest ideal curve was found, defined as the having the same shape as the prototype being copied, but potentially with a different scale (i.e. larger or smaller) and shift in location (relative to the bounding box). This ideal curve was found by varying the scale and location parameters to minimize the sum of the squared distance between the curve drawn (e.g. the dashed line in Fig. 2) and the ideal curve (e.g. the dotted curve in Fig. 2). The minimization was achieved using the simplex algorithm. We note that this is similar to Procrustes analysis, although we only consider translation and scale errors (and not reflection or rotation). Three measures of shape quality were defined for each drawing (Fig. 2) – *mean error:* the mean distance between the drawn shape and the ideal shape; *scale:* the difference in scale between the ideal shape and the prototype (1 = same size, 2 = double the size, 0.5 = half the size); *shift:* the distance in location between the ideal shape and the prototype. An example for a circle in shown in Fig. 2. It should be noted that the units for mean error and shift are cm, while scale is unitless.

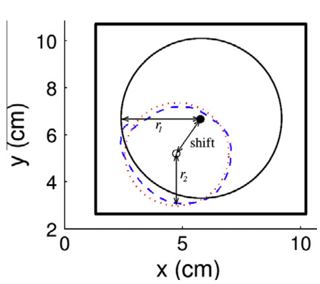


Fig. 2. Calculation of the measures quantifying the quality of the reproduction of a circle. The dashed curve is the shape drawn by the subject. The dotted line is the best-fit circle. The shift is the distance from the center of the template (solid circle centered inside a solid square) and the best-fit circle. The scale measure is the ratio of the radius of the best-fit circle (r_2) relative to the radius of the template (r_1). The mean error is the mean distance from the best-fit circle to the subject's curve.

For the path tracing task, the percentage of time inside/on the lines, and outside the lines were calculated, as well as the shortest distance from a center line.

2.4.2. Motor equivalence

As there is no standard measure of motor equivalence used in the literature, we defined a measure based on comparing variance within subjects (between the two postures) with variance between subjects. If motor equivalence is observed in this population, we expect that the difference in measures of graphic quality between the two postures for the same subject would be lower than the difference in graphic quality between the two postures for two randomly selected individuals from the same population. To test this, we used an approximate permutation test (Nichols and Holmes, 2002). That is, we randomly shuffled 10,000 times the subject labels and calculated the sum (over tasks) of the mean difference for each measure described above between the two postures, and compared this to the sum of the mean differences for the correct labeling. A *p*-value can be computed by calculating the proportion of randomly labeled trials that have a sum of the mean differences lower than the correct labeling.

2.4.3. Muscle activity patterns

The MVC value for each muscle was computed as the average of three peaks of the sEMG data, which differed by no more than 10% from one another. The mean root mean square (RMS) values of the sEMG data were normalized by the MVC value for each muscle.

Also, frequency analysis was performed on the EMG data collected during paths trailing, separately for each inclination. Median power frequency (MDF) was computed following short-time Fourier transform (STFT) spectrogram calculation using a Hanning sliding 500 ms window. Fatigue is associated with a compression of the power spectral density of the EMG toward the lower frequencies, so that a decrease in MDF corresponds to an increase in fatigue (Alfonsi et al., 1991).

2.4.4. Statistical analysis

Statistical analysis was performed using SPSS (V22, IBM, Armonk, NY, USA). To test differences between graphical product quality and muscle activity patterns in each surface orientation, mixed design MANOVAs were performed separately: We performed a mixed design MANOVA for the copying tasks to test the effect of tablet orientation on five dependent variables (movement time, shift, scale, mean error and number of acceleration zero crossings), with two intra-subject variables (object shape and tablet orientation) and one inter-subject variable (gender). We performed a similar analysis for the path tracing tasks, but with four dependent variables (movement time, percent time between the lines, distance from center and number of acceleration zero crossings). We performed a mixed design MANOVA on the muscle activity patterns data, with three dependent variables (the three muscles), and two intra-subject independent variables (task type, i.e. path tracing or copying; and tablet orientation) and one inter-subjects variable (gender). We repeated the MANOVA for normalized peak values, mean values, and MDF.

For the ANOVAs we tested the assumption of sphericity using Mauchly's test of sphericity. We used Greenhouse-Geisser correction when sphericity was violated. A level of $P < 0.05$ was considered statistically significant.

3. Results

3.1. Graphical product quality

An example of performance on the six tasks is depicted in Fig. 3. The performance measures for the copying tasks are presented in Fig. 4. The results showed a significant main effect of shape ($F(15,19) = 40.2$, $p < 0.001$) and tablet orientation ($F(5,29) = 2.82$, $p = 0.033$). There was no main effect for gender, nor any significant interaction. Univariate tests showed a main effect of shape on all five variables (movement time: $F(1.52,50.18) = 97.2$, $p < 0.001$; shift: $F(2.13,70.39) = 29.1$, $p < 0.001$; scale: $F(3,99) = 132.9$, $p < 0.001$; mean error: $F(3,99) = 87.6$, $p < 0.001$; zero-crossings: $F(3,99) = 87.6$, $p < 0.001$). Post-hoc pairwise comparisons showed that for movement time, all shapes were significantly different from each other (circle: 2.4 ± 0.2 s; square: 5.2 ± 0.3 s; wave: 3.9 ± 0.4 s; star: 10.9 ± 0.7 s). For shift, all pairs were significantly different, apart from the circle and the wave (circle: 0.81 ± 0.06 cm; square: 0.54 ± 0.05 cm; wave 1.2 ± 0.1 cm; star: 1.5 ± 0.1 cm). For scale, all pairs were significantly different, apart from the wave and the star (circle: 0.70 ± 0.02; square: 0.86 ± 0.03; wave 1.26 ± 0.03; star: 1.23 ± 0.03). For mean error, all pairs were significantly different, apart from the circle and the square (circle: 0.18 ± 0.01 cm; square: 0.20 ± 0.01 cm; wave 0.31 ± 0.01 cm; star: 0.42 ± 0.02 cm). For acceleration zero-crossings, all pairs were significantly different (circle: 9.6 ± 0.9; square: 23.5 ± 1.9; wave 16.9 ± 2.0; star: 46.2 ± 4.4). Surface orientation only had a significant effect on movement time ($F(1,34) = 25.68$, $p = 0.019$), with the movements slower in the horizontal condition (5.9 ± .4 s) compared to the vertical condition (5.3 ± .3 s), but not on shift, scale, mean error or zero-crossings.

Performance measures for the path tracing tasks are presented in Fig. 5. The results showed that there was a main effect only for shape ($F(4,30) = 109.1$, $p < 0.001$) and again there was no main effect of gender. Univariate tests showed a significant effect on percent between the lines ($F(1,33) = 38.3$, $p < 0.001$), with the broken line more accurate (97.8 ± 0.4%) than the curved line (87.8 ± 1.9%); on distance from center ($F(1,33) = 12.2$, $p = 0.001$), with the broken line closer (0.11 ± 0.02 cm) than the curved line (0.09 ± 0.04 cm). There was no main effect of shape on movement time or number of zero crossings. There was also no significant main effect of tablet orientation for the path tracing tasks.

3.2. Motor equivalence

To test for motor equivalence, we compared the variation within a subject between the two orientations, and compared it to the variation between subjects. We found that for all measures of graphical quality described above, the intra-subject variation was significantly lower than the inter-subject variation ($p < 0.001$).

3.3. Muscle activity patterns

There were no statistically significant differences in the normalized peak values of the three muscles. There was, however, for the mean values a main effect of tablet orientation ($F(3,24) = 9.76$,

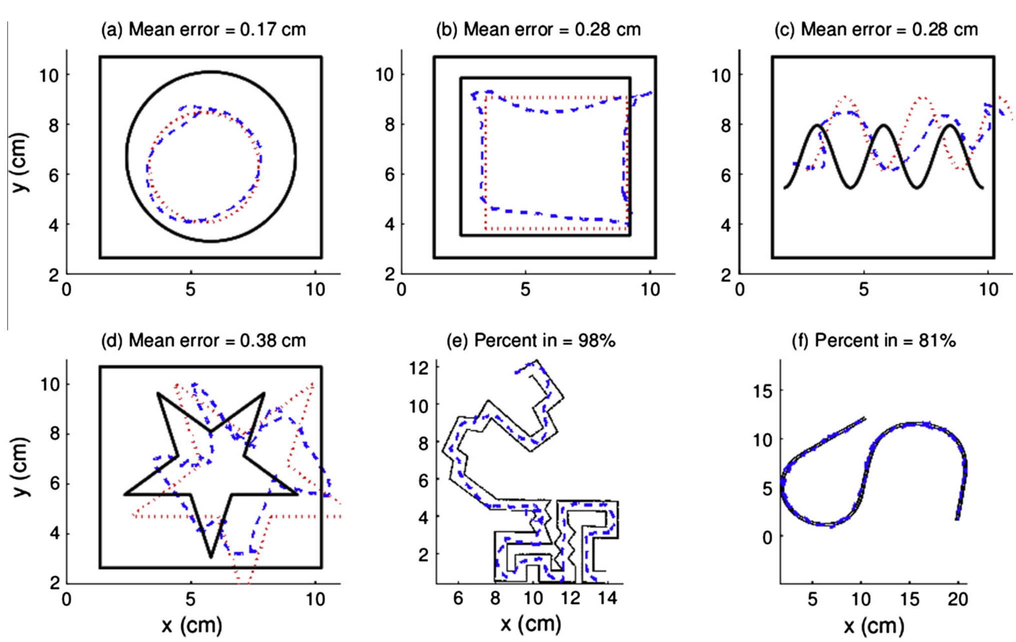


Fig. 3. Example of performance on the 6 tasks. For the copying tasks (a–d), the drawing produced (dashed line) is shown superimposed on the template (solid line). In the path tracing tasks (e and f), the solid lines show the boundaries, with the dotted line the performance. During production of the movements, the drawing produced by the subject was shown as a solid blue line. The distances are all relative to the lower-left corner of the tablet. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

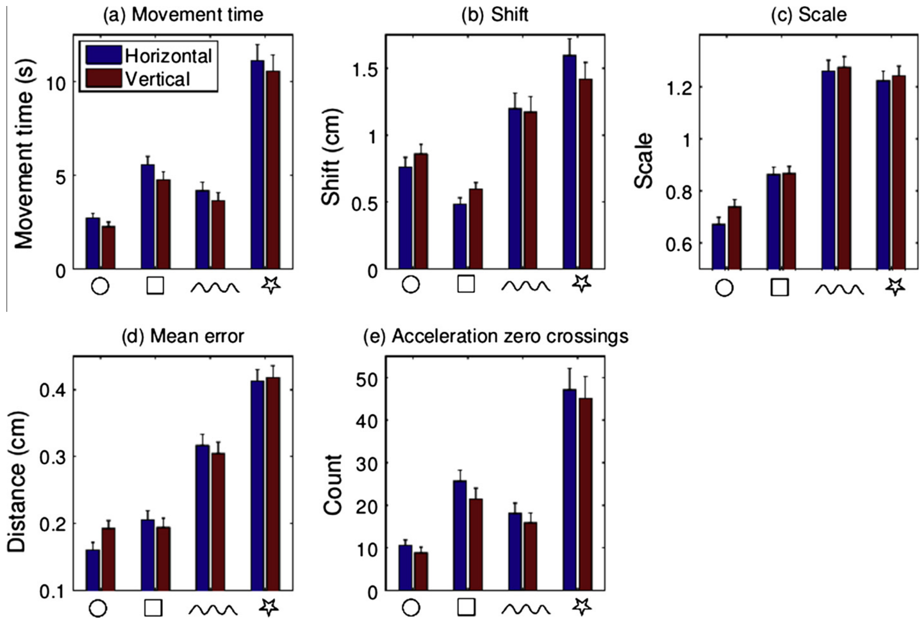


Fig. 4. Performance measures for the copying tasks. The bar graphs show the mean and standard error for copying the four shapes, for the (a) movement time, (b) shift (distance between center of the drawn shape and the template), (c) scale (ratio of the drawn shape to the template, >1 indicates the drawn shape is larger), (d) mean error between the best-fit and drawn shapes, (e) number of acceleration zero crossings.

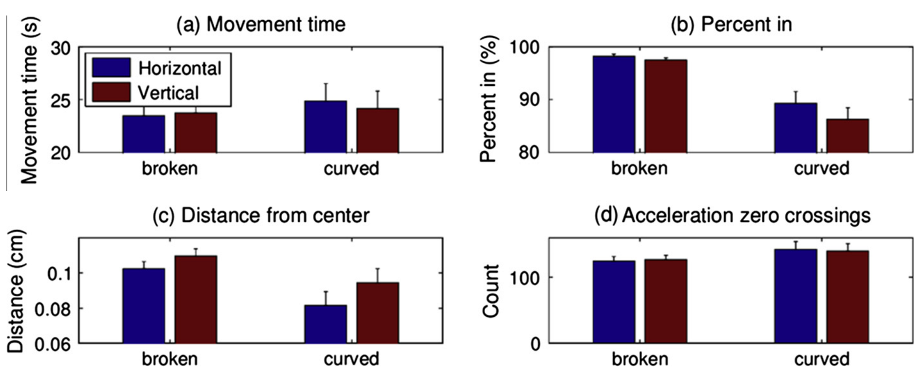


Fig. 5. Performance measures for the path tracing tasks. The bar graphs show the mean and standard error for the two tasks, for the (a) movement time, (b) percent time within/on the lines, (c) mean distance from the center, (d) number of acceleration zero crossings.

$p < 0.001$), and interactions of orientation and task type ($F(3,24) = 5.18$, $p = 0.007$), orientation and gender ($F(3,24) = 5.13$, $p = 0.007$) and orientation, task and type ($F(3,24) = 4.93$, $p = 0.008$), shown by the multivariate tests, and as depicted in Table 1. We followed this up with univariate tests to identify which muscles showed different patterns.

The normalized mean EMG activity in both the UT and BB were significantly greater in the vertical orientation (UT: median 7.60%; BB: median 1.67%) compared to the horizontal orientation (UT: median 6.46%; BB: median 1.48%) (UT: $F(1,27) = 12.15$, $p = 0.002$; BB: $F(1,27) = 13.19$, $p = 0.001$). There was a significant interaction of orientation and task for all three EMG signals (UT: $F(1,26) = 7.50$, $p = 0.011$, BB: $F(1,26) = 5.08$, $p = 0.033$, ECR: $F(1,26) = 7.19$, $p = 0.013$). Post-hoc paired tests showed that only for the path tracing task the normalized mean EMG activity was greater in the UT in the vertical orientation (median 7.83%)

Table 1
Median (25th–75th percentiles) of the mean recorded muscle activity normalized by maximal voluntary contraction (MVC) and presented in %MVC, for the three monitored muscles during shape copying or path tracing in the two inclination conditions. Also, the median (25th–75th percentiles) of the median power frequency (MDF) computed for the three monitored muscles during path tracing in the two inclination conditions.

	Shape copying (%MVC)		Path tracing (%MVC)		MDF (Hz)	
	Horizontal	Vertical	Horizontal	Vertical	Horizontal	Vertical
UT	6.55 (4.76–8.84)	7.41 (5.58–9.69)	**5.87 (3.94–7.97)**	**7.83*** **(5.88–10.27)**	107.3 (101.8–129.1)	107.5 (98.6–114.1)
BB	1.48 (1.14–2.59)	1.81 (1.33–3.16)	1.48 (0.89–2.32)	1.62 (1.23–3.77)	97.0 (90.2–118.0)	104.0(86.3–122.1)
ECR	2.17 (1.68–2.75)	2.08 (1.44–2.67)	**2.54 (1.69–3.15)**	**2.12*** **(1.612.55)**	**159.2 (138.8–171.7)**	**182.0*** **(158.5–196.2)**

UT = upper trapezius; BB = biceps brachii; ECR = extensor carpi radialis.
* $P < 0.05$.

compared to the horizontal orientation (median 5.87%), while in the ECR, the opposite pattern was observed (Table 1): greater EMG activation in the horizontal orientation (median 2.54%) compared to the vertical orientation (median 2.12%) for only the path tracing task. Normalized mean EMG activity in the BB in the path tracing task was greater in the vertical orientation (median 1.61%) compared to the horizontal orientation (median 1.50%), and showed the opposite pattern for the copying task, where the activity was greater in the horizontal orientation (median 7.14%) than in the vertical orientation (median 1.94%).

A significant interaction was also observed for orientation and gender for the UT ($F(1,26) = 5.77$, $p = 0.024$) and the BB ($F(1,26) = 11.0$, $p = 0.003$). Post-hoc tests showed that only for females the UT activity was higher for the vertical orientation (median 8.74%) compared to the horizontal orientation (median 5.97%). For the BB, the activity was higher for the vertical orientation for both males (median 1.53%) and females (median 3.10%) compared to the horizontal orientation (males: 1.38%; females:2.06%), however the difference between orientations was greater for the females.

A three-way interaction was observed only for the BB ($F(1,26) = 8.27$, $p = 0.008$). Post-hoc tests showed that this is due to the higher activity of BB in females for the vertical orientation in the path tracing task (median 3.15%) compared to the copying task (2.77%); whereas for the horizontal orientation, and for males for both orientations, there was higher activity during the copying task compared to the path-tracing task.

The results of the frequency analysis are presented in Table 1. The multivariate tests showed a significant main effect of tablet orientation ($F(3,30) = 4.70$, $p = 0.008$). The follow-up univariate tests showed that there is a main effect of MDF for the ECR, with the MDF value lower, i.e. greater fatigue, for the horizontal orientation (160 ± 6 Hz) compared to the vertical orientation (177 ± 6 Hz). No statistical differences were found between the MDF values of both the UT and the BB, and there was no main effect of gender.

4. Discussion

In this study, we performed a preliminary investigation into the basic mechanism of motor equivalence in children, during common everyday activities of drawing while sitting at a desk or while standing near a vertical drawing board. We used objective and precise means to quantify the graphical level of performance and muscle activity patterns to test the hypothesis that the level of performance in both cases would be similar, although the proximal muscles would be more activated and fatigued while drawing on the vertical surface in a standing position.

Our main findings support our hypothesis, showing differences in muscle activity patterns with no differences in graphical level of performance in 35 children drawing on two different conditions: sitting and drawing on a horizontal surface or standing and drawing on a vertical surface. Specifically, there was no difference in the quality of the graphical outcome between the two surface inclinations. In addition, a permutation test showed that the intra-subject variation in performance of the task for the two postures was significantly smaller than the inter-subject performance. This similarity in performance further supports our claim that the graphical performance in the two postures was similar despite the differences in muscles used.

Motor equivalence in five-to six- years olds was demonstrated in this study, as we observed that while the motor strategy differed between states, as was registered by the EMG, the graphic performance level was maintained. This agrees with previous studies showing spatial invariance in handwriting quality across different size ranges and task conditions (Rogers and Bryan, 1996; Thomassen and Hans-Leo, 1985). We found that the surface orientation had a significant effect on the time it took the subjects to complete the four shape copying tasks, which was longer when sitting at a desk. However, no difference in duration for completion was found in the longer path tracing task, analyzed for muscle fatigue. It would be interesting to compare these results with those of children with DCD, as it was reported that these children tend to take longer pauses (Prunty et al., 2013, 2014). In this study, during path tracing on a vertical surface, the normalized mean EMG activity of the UT and BB were significantly higher when compared to the horizontal surface, whereas the normalized mean EMG activity of the ECR was lower. Also, the significantly lower MDF values found for the ECR muscle during path tracing on the horizontal surface compared to the vertical surface suggests greater fatigue. These findings emphasize the different muscles activity patterns used in each condition. Not surprisingly, the wrist plays an important part in producing graphics on a horizontal surface. Although we recorded different physical strategies in performing the task on each inclination, on the cognitive aspect, we assume that a similar motor program was retrieved on both surfaces so that no cognitive surplus was required.

Some gender differences were observed in terms of the EMG activity, but not for the graphic quality. A previous study looking at a large number of children found differences in movement time between males and females when performing tracking, aiming and tracing tasks with a stylus on a tablet (Flatters et al., 2014a), with females being faster in the four to five year old group. This difference in movement time was not observed in this study, although this may be due to the smaller sample size. In terms of EMG activity, however, a number of differences were observed between the male and female subjects. These differences were manifested by a greater variety of EMG activity between tasks and postures for the female subjects compared to the male subjects, suggesting that the female subjects showed a wider range of motor strategies for the different tasks. The implication of these EMG differences in terms of movement and force production remains an interesting question for further study.

The main limitation of this study was the differences in postures between the horizontal drawing task, performed while the subject sat on a chair, and the vertical drawing task, performed while the subject was standing. This setup was chosen for our study protocol to best imitate the conditions in classroom or clinical settings. However, while in the sitting position, the subject may have rested one or both elbows and/or wrists on the table, thereby supporting the torso and relieving the gravitational workload demands from the proximal muscles. During the standing task, the child was subjected to various postural demands (Flatters et al., 2014b) as well as the demand to support the full weight of the limb, which might have influence the performance. Despite these postural differences, there were no significant differences in the graphic quality produced in the two different postures. It would be interesting to further explore how much of the differences in the muscle activation patterns observed in this study relate to the plane of movement and to what extent do they relate to the posture of the subjects. Second, the use of the electrodes taped to the skin might have influenced the movements of the subjects. In order to minimize this effect, each subject was asked to move the monitored limb about before recording commenced, in order to get accustomed to the stickers. Third, the friction properties of a stylus are different from that of a pen on paper (Wann and Nimmo-Smith, 1991). Last, in the shape copying tasks, the shapes are viewed from different vantage points. While standing, the shape was presented directly in front of the subject so that a circle would have appeared undistorted. However, while seated near a table, the subject might not have leaned forward to observe the shape directly from above so that a circle, for example, might have slightly been distorted to an ellipse. Despite these potential differences in the observation of the shapes, no differences in graphical quality were found.

5. Conclusions

In conclusion, the findings of this study suggest that although different muscle activation patterns are utilized by the children while drawing on horizontal and vertical surfaces, motor equivalence is observed, i.e. the graphic product performance level is maintained. Some gender differences were observed in terms of EMG activity, which suggest that female children at this age use a wider variety of muscle strategies. Further studies should explore the developmental trajectory of motor equivalence, and how it is affected in children with motor difficulties.

Conflict of interest

None.

References

Alfonsi E, Ricciardi L, Arrigo A, Lozza A, Sandrini G, Zandrini C, et al. Local venous lactate changes and spectral analysis of surface EMG during fatiguing isometric efforts in intrinsic hand muscles. Funct Neurol 1991;6(2):121–7.

Amundson S. Handwriting: evaluation and intervention in school settings. In: Case-Smith J, Pehoski C, editors. Development of hand skills in children. Rockville: AOTA Inc.; 1992. p. 63–78.

Atkeson C, Hollerbach J. Kinematic features of unrestrained vertical arm movements. J Neurosci: Official J Soc Neurosci 1985;5(9):2318–30.

Beery K. Administration, scoring, and teaching manual for the Beery-Buktenica developmental test of visual-motor integration with supplemental developmental tests of visual perception and motor coordination. New Jersey: Modern Curriculum Press; 1997.

Benbow M. Principles and practices of teaching handwriting. In: Henderson A, Pehoski C, editors. Hand function in the child. St. Louis: Mosby; 1995. p. 255–81.

Burden A. How should we normalize electromyograms obtained from healthy participants? What we have learned from over 25 years of research. J Electromyogr Kinesiol 2010;20(6):1023–35.

Deitz JC, Kartin D, Kopp K. Review of the Bruininks-Oseretsky test of motor proficiency, second edition (BOT-2). Phys Occup Ther Pediatr 2007;27(4):87–102.

Flatters I, Hill LJ, Williams JH, Barber SE, Mon-Williams M. Manual control age and sex differences in 4–11 year old children. PLoS ONE 2014a;9(2):e88692.

Flatters I, Mushtaq F, Hill LJ, Holt RJ, Wilkie RM, Mon-Williams M. The relationship between a child's postural stability and manual dexterity. Exp Brain Res 2014b;232(9):2907–17.

Frost LR, Gerling ME, Markic JL, Brown SH. Exploring the effect of repeated-day familiarization on the ability to generate reliable maximum voluntary muscle activation. J Electromyogr Kinesiol: Official J Int Soc Electrophysiol Kinesiol 2012;22(6):886–92.

Heriza C. Motor development: traditional and contemporary theories. In: Lister M, editor. Contemporary management of motor control problems: Proceedings of the II STEP Conference. Fredricksburg, VA: Bookcrafters Inc.; 1991. p. 99–126.

Hermens HJ, Freriks B, Disselhorst-Klug C, Rau G. Development of recommendations for SEMG sensors and sensor placement procedures. J Electromyogr Kinesiol 2000;10(5):361–74.

Judge S. Constructing an assistive technology toolkit for young children: views from the field. J Special Edu Technol 2006;21(4):17–24.

Linderman M, Lebedev MA, Erlichman JS. Recognition of handwriting from electromyography. PLoS ONE 2009;4(8):e6791.

Merton PA. How we control the contraction of our muscles. Sci Am 1972;226(5):30–7.

Naider-Steinhart S, Katz-Leurer M. Analysis of proximal and distal muscle activity during handwriting tasks. Am J Occupat Ther: Official Publ Am Occupat Ther Assoc 2007;61(4):392–8.

Nichols TE, Holmes AP. Nonparametric permutation tests for functional neuroimaging: a primer with examples. Hum Brain Mapp 2002;15(1):1–25.

Prunty MM, Barnett AL, Wilmut K, Plumb MS. Handwriting speed in children with developmental coordination disorder: are they really slower? Res Dev Disabil 2013;34(9):2927–36.

Prunty MM, Barnett AL, Wilmut K, Plumb MS. An examination of writing pauses in the handwriting of children with developmental coordination disorder. Res Dev Disabil 2014;35(11):2894–905.

Rastatter MP, McGuire RA, Bushong L, Loposky M. Speech-motor equivalence in aging subjects'. Percept Mot Skills 1987;64(2):635–8.

Rogers D, Bryan F. The objective measurement of spatial invariance in handwriting. In: Simner M, Leedham C, Thomassen A, editors. Handwriting and drawing research. Amsterdam: IOS press; 1996. p. 3–13.

Sporns O, Edelman GM. Solving Bernstein's problem: a proposal for the development of coordinated movement by selection. Child Dev 1993;64(4):960–81.

Sporrong H, Palmerud G, Kadefors R, Herberts P. The effect of light manual precision work on shoulder muscles – an EMG analysis. J Electromyogr Kinesiol: Official J Int Soc Electrophysiol Kinesiol 1998;8(3):177–84.

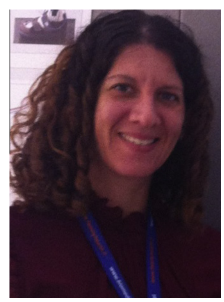
Thomassen A, Hans-Leo T. Time, size and shape in handwriting: exploring spatio-temporal relationships at different levels. In: Michon J, Jackson J, editors. Time, mind, and behavior. Berlin, Heidelberg: Springer; 1985. p. 253–63.

Turvey MT, Fitch HL, Tuller B. The Bernstein perspective: I. The problems of degrees of freedom and context-conditioned variability. In: Kelso JAS, editor. Understanding human motor control. IL: Champaign; 1982. p. 239–52.

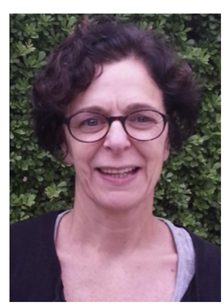
Wann J, Nimmo-Smith I. The control of pen pressure in handwriting: a subtle point. Hum Mov Sci 1991;10(2–3):223–46.

Wing AM. Motor control: mechanisms of motor equivalence in handwriting. Curr Biol: CB 2000;10(6):R245–8.

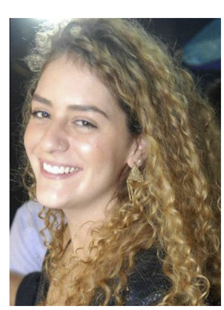
Yakimishyn JE, Magill-Evans J. Comparisons among tools, surface orientation, and pencil grasp for children 23 months of age. Am J Occupat Ther: Official Publ Am Occupat Ther Assoc 2002;56(5):564–72.



Sigal Portnoy received her B.Sc. in electronics engineering at Tel Aviv University, Israel, and her M.Sc. and Ph.D. studies in Biomedical engineering at the musculoskeletal biomechanics laboratory at Tel Aviv University, Israel. She is the scientific director of the gait and motion laboratory at the Hadassah medical center in Jerusalem, where she manages several researches that aim to quantify the effect of different treatment methods and procedures on the movement pattern of patients suffering from motor disabilities caused by neurological or orthopedic impairments. She is a lecturer at the Occupational Therapy Department at Tel Aviv University, where her lab is dedicated to the study of motor function and rehabilitation by means of biomechanical modeling as well as the design of diagnostic and treatment rehabilitation tools.



Limor Rosenberg, occupational therapist PhD. She received her PhD in 2011 from the Graduate School, Sackler Faculty of Medicine, University of Tel Aviv, Israel. She works as an occupational therapist at a multidisciplinary pediatric clinic for children with developmental disabilities, and she teaches and researches at the Department of Occupational Therapy, School of Health Professions, Sackler Faculty of Medicine, Tel Aviv University. Her main interests include personal and environmental factors restricting or enabling participation in children with and without disabilities.



Tal Alazraki, occupational Therapy graduate, class of 2014, Tel-Aviv University. Currently practicing as an occupational therapist in school of children with autism spectrum disorders and in a unique empowerment and support center of parents with learning disabilities, ADHD and adaptive challenges. Further on her career, she would like to deepen her experience with children's learning disabilities. Her goal is to focus mainly in developing therapy interventions that could improve function, capability and wellbeing.

Esti Elyakim, occupational Therapy graduate, class of 2014, Tel-Aviv University. She currently works at communication kindergartens through the Ashdod municipal/regional support center. Also, she works with children with developmental delay through the Magen Ha'Lev association.

Jason Friedman received a B.Sc in Computer Science from Monash University in Australia, and an M.Sc and Ph.D in Computer Science & Applied Mathematics from the Weizmann Institute of Science in Israel. He received postdoctoral training in the kinesiology department at the Pennsylvania State University, USA and in the cognitive science department at Macquarie University, Australia. He is currently a senior lecturer in the department of Physical Therapy and a member of the Sagol School of Neuroscience at Tel Aviv University, Israel. His research focuses on computational motor control, in particular modelling movements of the arm and fingers in typically developing populations and in individuals with motor disorders.