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Contactless Kinesthetic Feedback to Support Handwriting Using Magnetic Force

Georgios Korres, Wanjoo Park, and Mohamad Eid

Abstract—Handwriting is a fundamental human skill that is essential for communication yet is one of the most complex skills to be mastered. Pen-based interaction with touchscreen devices are increasingly used in digital handwriting practices to simulate pen and paper experience, but are mostly based on auditory-visual feedback. Given that handwriting relies on visual and motor skills, haptic feedback is recently explored to augment audio-visual systems to further support the handwriting process. In this paper, we present an assistive platform entitled KATIB (means *writer* in Arabic) that provides high fidelity kinesthetic feedback, in addition to audio-visual feedback, to support handwriting using magnetic forces. We propose novel contactless kinesthetic guidance methods, namely proactive and retroactive guidance, to guide the handwriting stylus along a desirable trajectory based on position control. Detaching the handwriting stylus from any mechanical device enables learners to have full control over grasping and moving at their own pace and style. The proposed platform is characterized for haptic interaction. Finally, a psychophysical experiment is conducted to validate that the kinesthetic guidance is perceivable and beneficial as a sensory feedback using a novel handwriting copy task. Contactless kinesthetic feedback seems to play a significant role in supporting digital handwriting by influencing the kinematics of the handwriting process.

Index Terms—Haptic Guidance, Handwriting assistive technologies, Evaluation/Methodology, User-centered Design.

1 Introduction

Handwriting is a core skill that humans must acquire to achieve academic success. However, the development of handwriting skills involves a large set of perceptual, cognitive, sensorimotor, memory and linguistic abilities to master. Consequently, the acquisition of handwriting involves a long, repetitive, and a complex learning process. With technological advances of digital tools, handwriting involves not only the practice with pen on paper, but also a variety of digital tools such as pen-like stylus or finger on a tablet surface [1]. Pen-based interaction with touchscreen devices is becoming increasingly popular due to its ability to simulate real-life handwriting while providing interactive, personalized, and multimodal feedback [2].

Two types of sensory feedback, namely visual and haptic, are naturally used in handwriting [3]. Visual feedback allows the writer to correctly link letters, stroke sequence for letters with multiple strokes, and words. Even though visual feedback does not seem to significantly influence the ongoing movement that generates the handwriting task, suppressing vision while writing improves fluency at the cost of accuracy and legibility [4]. On the other hand, haptic feedback is essential for controlling the kinematics and dynamics of handwriting movements. For example, it was found that the lack of haptic feedback while handwriting on a touchscreen device revealed a disturbance in the online regulation of initial motor commands (reflected through increased pen pressure and pen speed) [5].

Traditional assistive technologies for handwriting have focused primarily on visual feedback due to the maturity and low cost of visual displays. Recently there has been a trend to augment existing visual systems with haptic feedback to improve handwriting performance and/or learning outcomes [4] [6] [7]. An early study demonstrated that visuo-haptic feedback significantly improved the fluency of handwriting (faster movement, less velocity peaks and pen lifting). A subsequent study revealed a significant interaction between visual and kinesthetic feedback on hand movement control during handwriting [7]. Recent studies demonstrated that training with combined haptic and visual guidance on a touchscreen display improves the quality of handwriting in children [8] [6] [9].

Two classes of haptic feedback to support handwriting are distinguished: tactile feedback that informs the writer about the forces exerted during handwriting and kinesthetic feedback that conveys spatial, kinematic, and/or dynamic characteristics of handwriting movement [4]. A few studies examining the role of vibrotactile feedback, rendered through a vibration motor attached to the stylus, demonstrated improved handwriting performance [10] [11] [12] [13]. Supported by the fact that proprioceptive feedback is essential for controlling the kinematics and dynamics of handwriting movements [14], most existing haptic-based handwriting platforms are based on kinesthetic feedback. A common approach is to mechanically attach a pen-like stylus to a robotic arm to provide physical guidance along the handwriting trajectory [15] [16] [17].

Kinesthetic feedback devices that are based on mechanical attachment of the stylus to a robotic arm raise several ergonomic/usability concerns such as mechanical friction, movement inertia, guidance bulkiness, visual occlusion, and grip inflexibility. A recent trend is to provide kinesthetic feedback in a contactless manner without direct skin contact based on magnetic forces [18]. Magnetically-driven kinesthetic feedback is desirable since magnetic forces can be felt

• *G. Korres, W. Park, and M. Eid are with the Engineering Division, New York University Abu Dhabi, United Arab Emirates.*
E-mail: mohamad.eid@nyu.edu, see https://wp.nyu.edu/aimlab/

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at the tip of the stylus without being mechanically attached to a robotic arm.

This paper presents the development, characterization, and evaluation of a system that provides high-fidelity kinesthetic feedback using magnetic forces for pen-based interaction with touchscreen devices to achieve the ergonomic benefits associated with freely moving the handwriting stylus. The contributions of this study include:

- Developing high-fidelity contactless kinesthetic handwriting feedback system using magnetic force, based on position control,
- Characterizing the proposed system as a haptic interface in terms of the magnetic force interaction between the stylus and the writing surface, the maximum force, and operating workspace, and
- Validating the quality of the contacless kinesthetic feedback using magnetic force through a psychophysical experiment with human subjects.

The remainder of the paper is organized as follows. Section 2 analyzes the related work for contactless kinesthetic feedback for supporting handwriting. Section 3 presents the KATIB platform, including the system architecture as well as the software and hardware components. In section 4, the KATIB hardware is characterized as a kinesthetic interface, including the maximum and quality of magnetic force, the active workspace, and the effects of static tilting of the stylus. Section 5 presents a psychophysical experiment to evaluate the quality of the haptic feedback in a novel handwriting copy task. Finally, section 6 summarizes the findings and provides directions for applications in handwriting learning and rehabilitation.

2 RELATED WORK

To provide contactless kinesthetic feedback, Lorentz magnetic levitation has been pursued for many years [19] [20], with commercially available devices such as the Maglev 200^{TM} by Butterfly Haptics [1]. These devices are typically used for displaying multiple degrees-of-freedom force feedback in 3D virtual environments or tele-operation, and are common in medical simulation [21]. However, these systems are not suitable for touchscreen devices due to their complexity and high cost.

Providing kinesthetic feedback at or near the surface of a touchscreen device attracted attention to enhance the interaction with the finger or a stylus for applications in handwriting, sketching, drawing, among others. A common approach is to utilize a 2D array of electromagnets to guide users to appropriate screen locations [22]. Examples of such technique include Actuated Workbench [23], Proactive Desk II [22], and Fingerflux [24]. For example, FingerFlux combined electromagnetic actuation with a permanent magnet attached to the user's finger to guide the user's finger to appropriate locations on a touchscreen device [24]. However, this approach is not suitable for handwriting tasks due to its low spatial resolution, which is limited by the number of electromagnets. Furthermore, the complex, nonlinear interactions between multiple electromagnets makes it challenging to accurately control the forces applied to the tip of the stylus.

1. https://butterflyhaptics.com/products/

An alternative approach involves attaching a single electromagnet to the end effector of a two degrees-of-freedom motorized linkage mechanism that is placed underneath the writing surface to provide attractive or repulsive force feedback at the tip of the stylus [25] [26]. As the linkage mechanism moves the electromagnet along a desired trajectory, it drags the stylus through magnetic forces along the same trajectory. An example of this approach is the dePENd system where two magnets are attached to two electric actuators, where the actuators slide the magnets along the x and the y directions to control the position of a third magnet that is placed underneath the writing surface [25]. Another study utilized a bi-axial linear stage with the electromagnet attached to its end effector to control the position of the stylus [26]. Pull-back forces are rendered using a closed-loop time-free approach to minimize the error between the stylus position and the desired trajectory.

The proposed system differs significantly in the fidelity of the kinesthetic feedback. The system utilizes a rotating permanent magnet to actuate the stylus tip by enabling or disabling the kinesthetic feedback. Compared to electromagnets, permanent magnets provide stronger magnetic force due to the higher concentration of magnetic flux at the actuation point. Furthermore, the heating effects after continuous use of the electromagnet weakens the magnetic flux and thus the magnetic force. Finally, in order to programatically control the magnetic force, the permanent magnet is mounted on a rotating platform to control the intensity of the magnetic force, which paves the way for developing multiple kinesthetic feedback guidance methods.

3 KATIB PLATFORM

Figure 1 shows the software and hardware components of the KATIB platform.

Fig. 1: KATIB platform prototype.

3.1 KATIB System Architecture

KATIB system is designed to facilitate multimodal communication of handwriting skills where an instructor may use

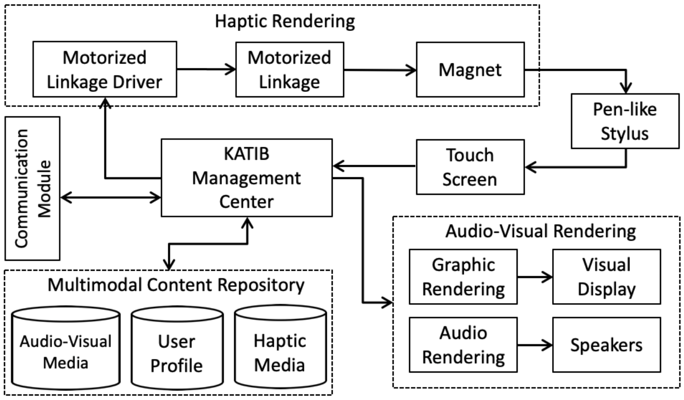

Fig. 2: KATIB system architecture.

input devices (such as a tablet) to record handwriting tasks and share with learners who play back the visual, auditory, and haptic properties of the designated handwriting task. The system continuously evaluates the handwriting of the learner and provides appropriate feedback to the learner as well as to the instructor.

A schematic diagram of the KATIB architecture is shown in Figure 2. The architecture comprises three major sub-systems: Haptic Rendering, Audio-Visual Rendering, and Multimodal Content Repository. The KATIB management center coordinates with the three sub-systems to provide synchronized recording/playback of haptic-audio-visual contents. The Communication Module enables users to share handwriting tasks over a computer network (such as an instructor supporting a learner or collaborating learners). Finally, the Multimodal Content Repository stores the visual, auditory, and haptic properties of all handwriting tasks that are available for the learners.

3.2 Graphical User Interface Design

Even though the ultimate goal is to develop two interfaces, one for the instructor to upload handwriting tasks and review learner's performance and one for the learner, the current implementation is focused on the learner's interface. As shown in Figure 1, the learner's graphical user interface consists of four parts: (1) a control menu on the left, the active handwriting area in the middle, a visual preview of the handwriting task on the right, and the exit button at the top-right. The control menu comprises of three buttons organized top to bottom, the erase button to delete an existing handwriting in the active area, the open button to load an existing handwriting task, and the play button to initiate the guidance.

A secondary interface, named the configuration GUI, is utilized to customize how the kinesthetic, audio, and visual feedback are presented to the learner. Three kinesthetic feedback modes are available, namely no feedback, proactive feedback, and retroactive feedback. The audio feedback can be turned on or off. Finally, the visual feedback provided in the active handwriting area can be turned on or off, presented in synchronization with the haptic guidance, or played as an animated preview before the user starts executing the handwriting task. The ability to configure multimodal feedback during handwriting allows learners to personalize feedback depending on their learning style/needs.

3.3 Haptic Guidance

Many techniques for haptic guidance to support handwriting are explored in previous studies [27] [28] [9]. KATIB platform supports two types of kinesthetic feedback, namely proactive guidance and retroactive guidance. Both techniques are based on controlling the position of the end effector. Proactive guidance, sometimes referred to as full haptic guidance, takes a leading role in the handwriting trajectory whereas the learner follows the trajectory through the visual/position guidance. As elaborated using Algorithm 1, the proactive guidance is activated once the learner places the stylus at the starting point of the trajectory (which is visually displayed). The algorithm retrieves the next position the learner must move to along the handwriting trajectory and applies maximum magnetic force to slide the stylus to that position. Once the stylus is confirmed in the new position, the algorithm selects the following position and applies maximum force to move to that position, and so on. In this case, the user continuously feels force feedback to swiftly move their hand along the handwriting trajectory.

Algorithm 1 Proactive guidance.

```
while poitnts#>0 do
    if StylusIsActive AND ||Tip_Loc − Point_Loc||_L2 < ϵ then
        points# =points# − 1
        Move_End_Effector(points#)
        Display_Dot(points#)
    else
        blink_Dot(points#)
    end
end
```

With retroactive guidance (sometime referred to as partial guidance), the user is free to move the stylus along the handwriting trajectory so that kinesthetic feedback is provided only when a significant deviation between the current and desired trajectory (position) is observed. Kinesthetic force is applied to bring back the learner to the desired trajectory and thus minimize the movement error. This guidance method is interactive by nature as it is activated only when an error in handwriting trajectory is detected. The retroactive method is elaborated in algorithm 2.

Algorithm 2 Retroactive guidance.

```
while poitnts#>0 do
    if StylusIsActive AND ||Tip_Loc − Point_Loc||_L2 < ϵ then
        points# = points# - 1;
        MagnetActive(FALSE)
        Move_End_Effector(points#)
        Display_Dot(points#)
    else
        MagnetActive(TRUE)
        blink_Dot(points#)
    end
end
```

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3.4 2 DoF Parallel Manipulator

The geometry of the 2 DoF parallel manipulator is presented in Figure 3. In order to calculate the coordinates of the end effector E, the forward kinematics need to be solved using equations 1 and 2 and in order to calculate the motor angles $\theta_1,\ \theta_2$ of the parallel manipulator with respect to the end effector placement, the inverse kinematics must be solved according to equations 3 and 4.

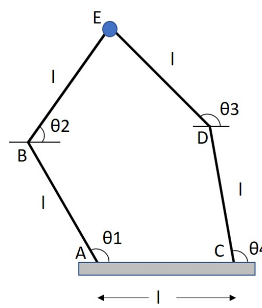

Fig. 3: The geometry of the Parallel Manipulator. All lengths are equal to l. The forward and inverse kinematics are solved with respect to the end effector E and the actuator angles $\theta_1,\ \theta_2$.

$$x_E = l\left[1+\cos\theta_4+\cos\left(2\arctan\left(\frac{-\beta\pm\sqrt{a^2+\beta^2-\gamma^2}}{\gamma-\alpha}\right)\right)\right] \quad (1)$$

$$y_E = l\left[\sin\theta_4+\sin\left(2\arctan\left(\frac{-\beta\pm\sqrt{a^2+\beta^2-\gamma^2}}{\gamma-\alpha}\right)\right)\right] \quad (2)$$

with $\alpha,\ \beta,\ \gamma$ given by:

$$\alpha = 2l^2\left(1+\cos\theta_4-\cos\theta_1\right)$$

$$\beta = 2l^2\left(\sin\theta_4-\sin\theta_1\right)$$

$$\gamma = 3l^2+2l^2\left(\cos\theta_4-\cos\theta_1-\cos\left(\theta_4-\theta_1\right)\right)$$

$$\theta_1 = 2\arctan\left(\frac{-\beta'\pm\sqrt{\alpha'^2+\beta'^2-\gamma'^2}}{\gamma'-\alpha'}\right) \quad (3)$$

$$\theta_4 = 2\arctan\left(\frac{-\epsilon'\pm\sqrt{\delta'^2+\epsilon'^2-\zeta'^2}}{\zeta'-\delta'}\right) \quad (4)$$

with $\alpha',\ \beta',\ \gamma',\ \delta',\ \epsilon',\ \zeta'$ are given by:

$$\alpha' = -2lx_E\ ,\ \beta' = -2ly_E\ ,\ \gamma' = x_E^2+y_E^2$$

$$\delta' = 2l(-x_E+l)\ ,\ \epsilon' = \beta'\ ,\ \zeta' = \gamma'+l^2-2lx_E$$

The forward kinematics equations can be used to calculate the working space of the system while the inverse kinematics equations will be used to steer the end effector to the desired position.

3.5 Magnetostatic Force Model

In magnetostatic analysis, the magnetic field is calculated under the assumption of a steady current. The magnetostatic equations can be derived from Maxwell's equations with the assumption that the charges can be either fixed or moving with a steady current J. In this case, Maxwell's equations can be split into two pairs of equations: two equations for the electric field (electrostatics) and two equations for the magnetic field (magnetostatics). In a magnetostatic analysis, the magnetic vector potential (MVP) $\mathbf{A}$ is defined such that $\mathbf{B}=\nabla\times\mathbf{A}$, then the magnetostatic response approximation of Maxwell's equations for a steady current density distribution $\mathbf{J}$ is given by:

$$\nabla\times\left(\mu^{-1}\cdot\nabla\times\mathbf{A}\right)=\mathbf{J} \quad (5)$$

where $\boldsymbol{\mu}$ is the magnetic permeability tensor which relates the magnetic flux density $\boldsymbol{B}$ to the magnetic field $\boldsymbol{H}$ through the constitutive equation $\boldsymbol{B}=\boldsymbol{\mu}\cdot\boldsymbol{H}$.

The variation formulation of equation 1 which will be used by Finite Elements solver is given by:

$$\int_V \nabla\times\delta\mathbf{A}\cdot\left(\mu^{-\mathbf{1}}\cdot\nabla\times\mathbf{A}\right)dV = \int_V \delta\mathbf{A}\cdot\mathbf{J}dV + \int_S \delta\mathbf{A}\cdot\mathbf{K}dS \quad (6)$$

where $\delta\mathbf{A}$ is the variation of MVP and $\mathbf{K}$ is the tangential surface current density which is applied at external surfaces.

The magnetic force due to a non uniform magnetic field can be calculated through the following equation:

$$\mathbf{F}=\nabla\left(\mathbf{m}\cdot\mathbf{B}\right) \quad (7)$$

whereas $\mathbf{m}$ is the magnetic moment vector. In case of a permanent magnet the magnetic moment can be expressed through the residual flux density of the magnet B_r as:

$$\mathbf{m}=\frac{1}{\mu_0}\mathbf{B}_r V \quad (8)$$

The magnetostatic analysis provides a useful test-bench for the KATIB platform since many combinations of different types and geometries of candidate magnets can be tested before their adoption. Furthermore, it provides a good approximation of the resulting magnetic force for various tilt angles and displacements of the magnets as presented in the following sections. A computational approximation is provided, using the ANSYS magnetostatic FEM solver as shown later in Figure 7, to calculate the magnetic force as a function of the position vector.

3.6 Hardware Implementation

The hardware system comprises a pen-like stylus equipped with stackable magnets, a low-cost resistive sensing touch-screen with a visual display to record interactions between the active surface and the magnetic stylus, a rotating magnet underneath the screen that is attached to the end-effector of a 2 DoF parallel manipulator mechanism, and a single board ARM CPU that runs a GUI application which provides audio, visual, and haptic feedback to the user. A snapshot of the hardware design is shown in Figure 4.

The KATIB hardware is implemented on a Raspberry Pi 3 B+ single board computer hosting an 1.4GHz 64-bit

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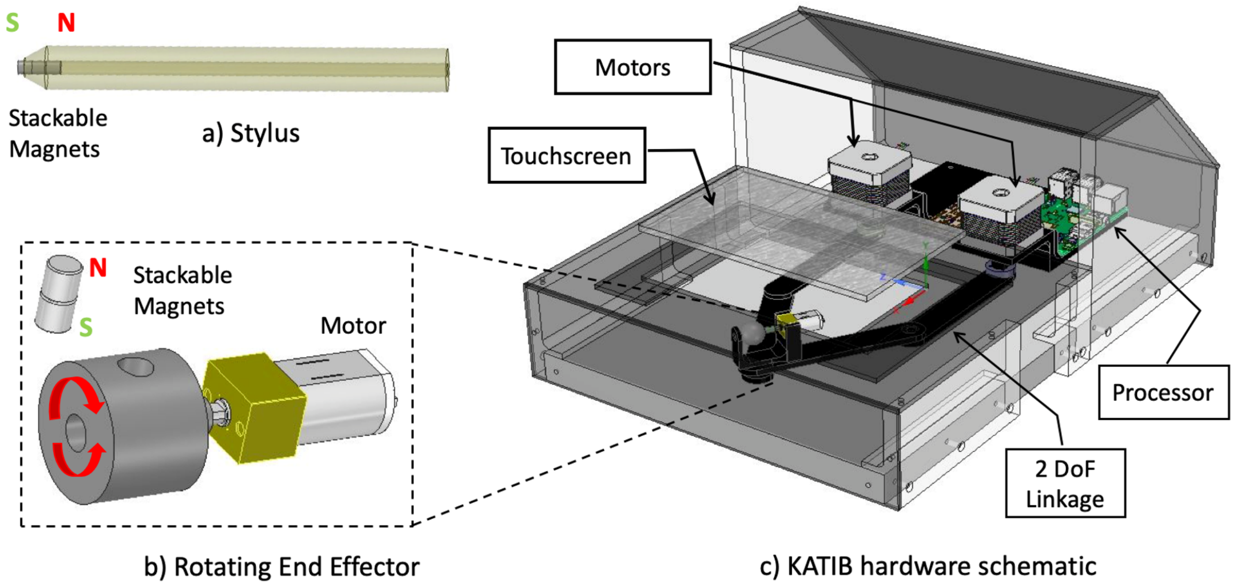

Fig. 4: Schematic diagram for the hardware design. a) the magnetic stylus, b) the rotating end-effector, and c) the 2 DOF parallel manipulator with the touchscreen and the controllers. Relative re-scaling between modules has been imposed for demonstration purposes. N and S represent the north and south poles respectively.

quad-core Broadcom Arm Cortex A53-architecture which is running Linux software. It drives two NEMA17 stepper motors equipped with a 5:1 planetary gearbox. The stepper motors are controlled with a PID position feedback controller based on the uStepper driver platform which is using an ATMEL ATMEGA328 MCU, a Trinamic TMC5130 Motor Driver and the AEAT8800-Q24 Hall effect encoder by Broadcom. The end effector rotates by the use of a custom motor control comprised of a 15k RPM micro DC motor with a 300:1 reduction gearbox and with a quadrature hall effect encoder mounted on its rear shaft which is driven from the DRV8838 driver by Texas Instruments and the ATMEGA328 by ATMEL. The Raspberry PI is also connected to a generic 640×480 TFT display which is driven by a generic HDMI-TFT driver. A resistive touchscreen that is controlled by the MICROCHIP AR1100 touchscreen controller is placed at the top of the display. The hardware implementation is shown in figure 5.

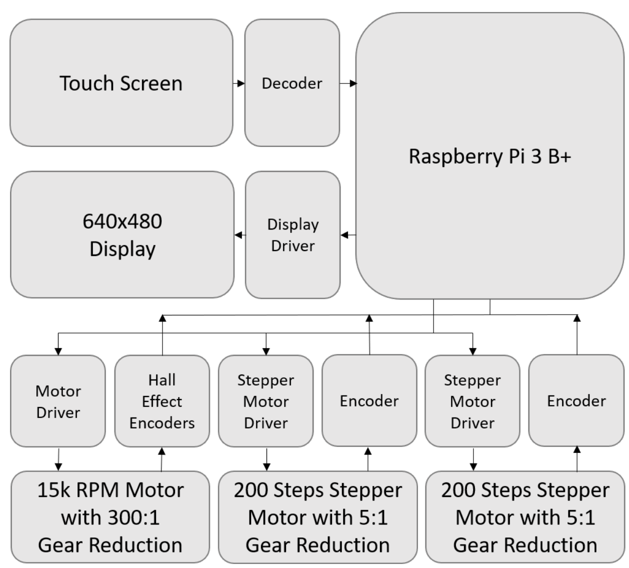

Fig. 5: KATIB hardware implementation.

4 Kinesthetic Feedback Characterization

4.1 Magnetostatic Force Analysis

The magnetic force that is acting on the stylus can be calculated according to equation 7, from the derivation of the magnetic field distribution on a specific geometry and material configuration (end effector position, glass screen, stylus magnet) and for a steady current, which is equal to zero for the particular case. The ANSYS Magnetostatic Analysis module can be used to solve for the magnetic field distribution for the different displacements and tilt angle of the stylus. The geometry that was used in the particular analysis consists of a stack of 2 cylindrical magnets which represents the stylus (5×5 mm and 2×2 mm respectively) and one cylindrical (5×5 mm) magnet which represents the end effector. The two magnets are separated by a surface of 4 mm thick glass material ($\mu_{r/glass} = 5$). Simulated air was used on the volume which encloses the whole structure ($\mu_{r/air} = 1$). The simulated magnetic material was Neodymium N42 (NdFeB) with its residual induction being at 1300 mT and coercive force being at 955 KA/m. In order to derive an accurate approximation the meshed geometry was refined around the main interaction region of the two magnets. The resulted meshed geometry of the model comprised of about 250k elements. Finally, the simulation was repeated for the different translation and tilt configurations of the stylus and end effector. The tangency between the base of the stylus magnet (top) and the glass surface defined the tilt angle. The total magnetic flux density distribution with respect to distance between the two magnets is shown in Figure 6.

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In order for the moving magnet to drag the stylus along the handwriting trajectory, the lateral attraction force between the magnet and the stylus has to overcome the static friction fs between the stylus and the writing surface. Figure 7 (left) demonstrates how the normal and lateral forces vary as the distance between the driving magnet and the stylus increases. For the particular setup we have, a maximum lateral force of 0.43 N is achieved at 3.5 mm away from the driving magnet. This is clearly sufficient force to move the stylus since the static friction is much smaller. It must be noted that this is an extreme case and in reality the user is holding the stylus and assumed to apply some forces along the desired trajectory. Also, while the user is grasping the stylus there is a tilt angle to reduce friction effects.

Another interesting phenomenon to study is the effect of tilting the stylus on the rendered magnetic forces (users might use the stylus at various tilting angles depending on their grasping habits). Consequently, the effects of tilting the stylus on the amplitude of the magnetic force is studied. As shown in Figure 7 (middle), it is clear that tilting the stylus up to 40° from the normal direction would results in a negligible lateral force. It is worth noting that the intensity of the magnetic force is dependent on the type of Neodymium magnet and the stackable magnets used in the stylus. Figure 7 (right) shows the maximum intensity of the lateral and normal magnetic forces for a range of Neodymium magnet types that are commercially available. Depending on the application needs, a proper Neodymium type magnet as well as a specific number of stackable magnet can be used to provide a target force.

4.2 Kinesthetic Feedback Workspace Analysis

The kinesthetic feedback workspace is defined by the permanent magnet position, which is derived from the two DOF parallel manipulator and is calculated by solving the

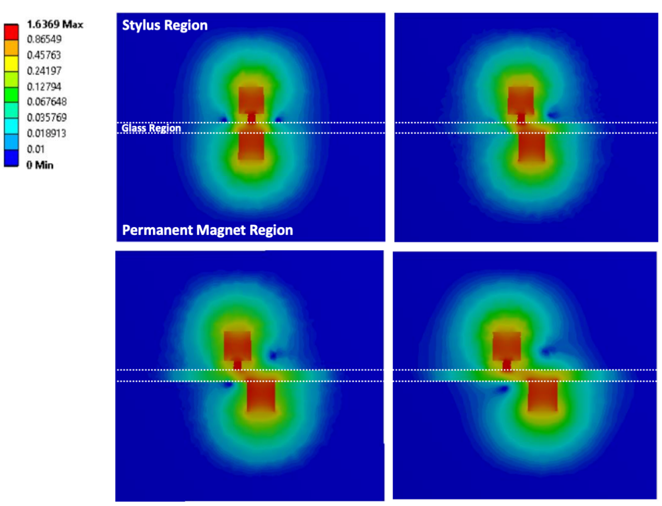

Fig. 6: The total magnetic flux density [T] as a function of the horizontal displacement between the handwriting stylus and the driving magnet. The simulation involves Neodymium magnet, glass, and air with corresponding magnetic permeability. From left to right and from top to bottom by 2 mm step. (6 mm to 0 mm).

forward kinematics problem (using equations 1 and 2). The current implementation utilized stepper motors that can be driven in up to 16 micro-steps, and with a planetary gearbox of 5:1 reduction rate, the final number of steps per motor shaft revolution is 16000 steps. A MATLAB scrip was developed to solve the kinematic problem for the workspace given a range of -45 to +45 degrees per motor and 100 mm as the length of each parallel manipulator segment. The workspace for the device was found to be 80 mm by 60 mm (width by height), which is sufficient for most handwriting applications. A visual representation of the exact kinesthetic feedback workspace is shown in Figure 8.

4.3 Quality of Kinesthetic Playback

The quality of kinesthetic playback is evaluated by placing the handwriting stylus at the starting position of the handwriting task, let the proactive kinesthetic force move the stylus along the handwriting trajectory without the human holding the stylus, and calculate the average root mean square error (RMSE) between the stylus and the reference trajectories. The average RMSE was found to be less than 3 mm. Figure 9 shows a visual demonstration of the kinesthetic playback for three sample shapes.

5 Psychophysical Evaluation

The objective of the psychophysical experiment is to evaluate the effects of kinesthetic feedback to support the handwriting process with novel handwriting tasks.

5.1 Participants

We recruited 16 participants (9 male, age range 24-39) for this study. None of the participants had any known sensorimotor, developmental or cognitive disorders at the time of testing. All participants have confirmed unfamiliarity with the assigned handwriting task (Arabic letters) to ensure that participants relied on the sensory input through kinesthetic feedback while constructing the handwriting task. Written informed consent was obtained from all participants. The study was approved by the Institutional Review Board for Protection of Human Subjects at New York University Abu Dhabi (Project # HRPP–2020–12).

5.2 Experimental Task and Protocol

In this experiment, participants completed a handwriting copy task for Arabic letters under two conditions: no kinesthetic feedback and with kinesthetic feedback. Twenty Arabic letters, divided into five difficulty levels, were used in the experiment. Difficulty levels were determined with the help of an Arabic handwriting expert based on variations in the projection axis (horizontal vs. vertical), aperture (open vs. closed), and extension (low vs. high) [7].

The task started by visually animating a randomly selected letter that the participant must copy. Once the animation is completed, the participant was instructed to write the corresponding letter where kinesthetic feedback was randomly turned on or off. Proactive (or full) kinesthetic guidance is utilized in this experiment. Participants were given the opportunity to replay the letter animation multiple times before writing it. Participants were instructed to

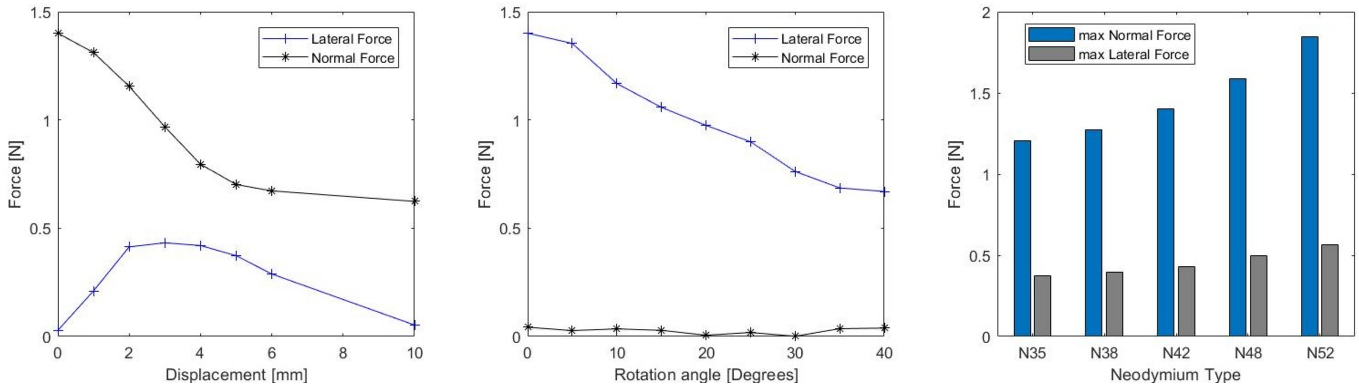

Fig. 7: Magnetostatic force analysis: (left) normal vs. lateral forces between the stylus and the magnet, (middle) normal and lateral force against tilt angle, (right) normal and lateral force magnitude for different Neodymium magnet types.

be as accurate as possible with both the spatial (follow exact trajectory) and temporal (same speed of the animated task) properties of the task. While writing, participants could see their handwriting rendered on the screen in real-time. The time stamp, position and feedback state (kinesthetic feedback on or off) were recorded during the handwriting task. Note that the visual model of the handwriting task was available through the preview area while performing the handwriting task, in order to minimize the effects of visual spatial memory.

As for the experimental protocol, participants performed the copy task individually in a quiet room. After a brief introduction about the experiment and the setup, participants were asked to read and sign the consent form. Then, a short training session was administered in order to familiarize participants with the setup and the guidance conditions (with/without kinesthetic feedback). Every participant completed a total of 40 copy tasks; five difficulty levels, four letters from each difficulty level, and two conditions (with or without kinesthetic feedback). The copy tasks were presented in a random order to avoid any short-term memory effects. No time limit was imposed on participants to complete the copy task. Once all copy tasks are completed, participants were asked to complete a questionnaire about their experience with the KATIB platform.

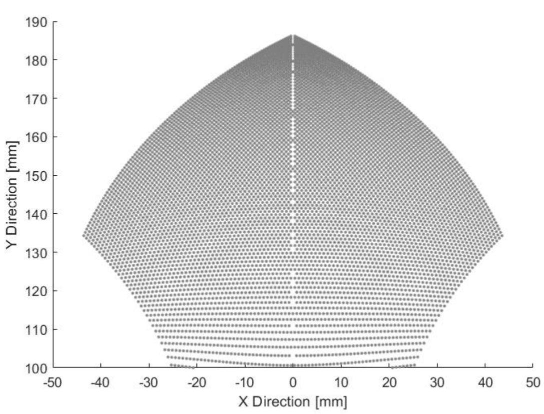

Fig. 8: Kinesthetic feedback workspace. The 2 DOF parallel manipulator can produce 10 times the resolution presented on this graph (based on the stepper motors resolution). The graph resolution was reduced for the purpose of clarity.

5.3 Results and Discussion

To analyze the effects of kinesthetic feedback on the handwriting kinematics, two kinematic variables were considered: the spatial accuracy measured through the RMSE error and the temporal accuracy through the task completion time (TCT). The data was analyzed using t-test statistical method after confirming normal distribution (Kolmogorov-Smirnov normality test).

The average RMSE for the copy tasks was calculated as follows: All copy tasks that participants completed were stacked, averaged (kappa-sigma clipping approach [29]) and normalized for each letter for the two conditions (with or without kinesthetic feedback), for the five difficulty levels. The RMSE for each letter stack was calculated against the reference letter that participants were asked to copy during the experiment. As summarized in Figure 10, the resulting RMSE was significantly lower for all difficulty levels kinesthetic feedback was turned on while handwriting (t-test, $p < 0.01$). This demonstrates that the kinesthetic feedback was clearly perceivable and significantly changed the handwriting kinematics.

Participants were instructed to perform the copy task not only to the spacial characteristics of the handwriting trajectory but also to the temporal properties. The animation of each letter was set to 10 seconds and participants were asked to complete the copy task as closely to 10 seconds as possible. As shown in Figure 11, participants had a task completion time closer, on average, to the 10 seconds target when kinesthetic feedback was turned on. Therefore, kinesthetic feedback supported the temporal properties of the handwriting process.

We also analyzed the questionnaire. Four questions were asked. (Q1) prompted the user to rate their knowledge of Arabic letters. Results confirmed that participants were completely unfamiliar with Arabic letters (average rating was 8.9%). Questions (Q2), (Q3), and (Q4) were used to evaluate the quality of user experience using two variables: the handwriting ergonomics (Q2) and the quality of kinesthetic feedback (Q3, Q4). The ergonomic evaluation

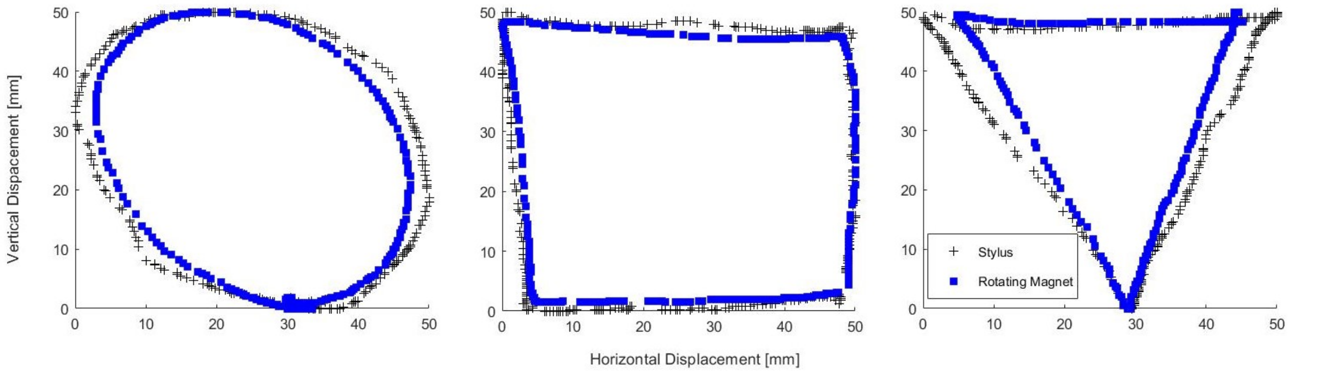

Fig. 9: Haptic playback for sample shapes. In blue the end effector coordinates while animating each shape and in black the stylus movement on the touchscreen as a response on the magnetic force.

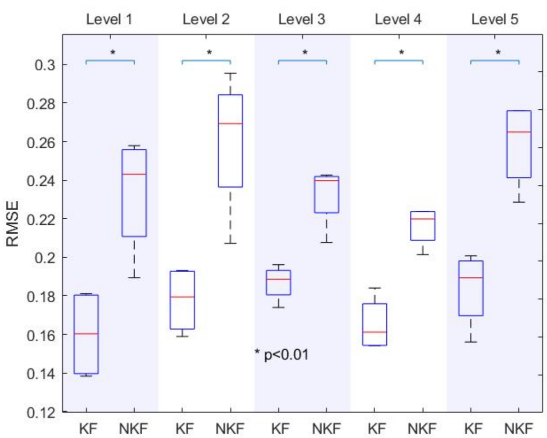

Fig. 10: Mean RMSE for the five difficulty levels with kinesthetic feedback (KF) and with no kinesthetic feedback (NKF), t-test, $p < 0.01$.

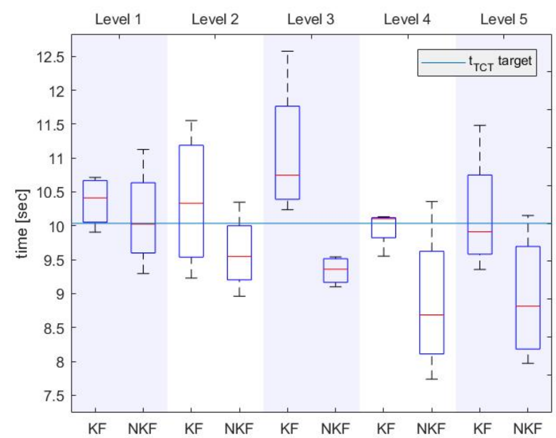

Fig. 11: Mean task completion time for the five difficulty levels, with Kinesthetic feedback (KF) and with no kinesthetic feedback (NKF).

included specifically the stylus control, fatigue and the integration of kinesthetic and visual feedback. Participants were asked to assess the ergonomics of the KATIB platform on a scale (0-100). The mean ergonomics rating was 59%. Most participants indicated that the free stylus control significantly improved the ergonomics of the platform. Some participants reported that the kinesthetic feedback was a little confusing at the beginning as it was a novel experience for them.

The quality of kinesthetic feedback was assessed by rating the clarity of kinesthetic feedback while handwriting (Q3). Most participants thought that the kinesthetic guidance was clearly perceivable (average clarity rate was 67%). This finding was complemented by another question (Q4) about the percentage of times participants thought kinesthetic feedback was applied. The average rating was 49%, which is about the percentage of times kinesthetic feedback was provided (the exact was 50%). This implied that participants were able to accurately detect when kinesthetic feedback was provided.

A few limitations of the KATIB platform should be noted. First, extending the active workspace where kinesthetic feedback is provided necessitates bulkier parallel manipulator, which increases the size of the device and thus reduces it's portability. Furthermore, even though the guidance force is clearly perceivable and adequate for handwriting applications, it may not be suitable for other appli-

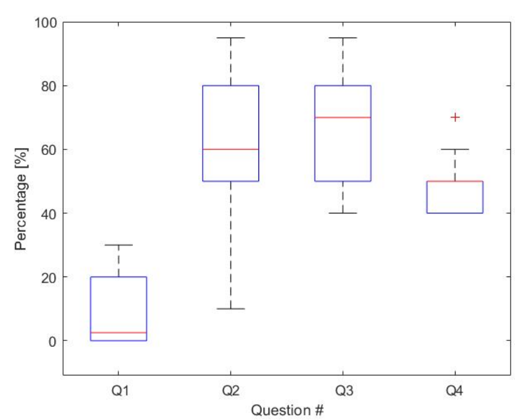

Fig. 12: Summary of the subjective evaluation questions.

cations (such as medical procedures). The proposed system is unable to provide torque feedback, which might be useful to some applications. Finally, the current magnetostatic simulation is not capable to accurately analyze the effects of the generated torque when the stylus is tilted. A comprehensive analysis to explore the effects (if any) of the generated torque on the users' performance is desirable.

6 Conclusions

In this paper, we proposed a high-fidelity contactless kinesthetic feedback system to support handwriting. A permanent magnet was utilized to provide strong and highly concentrated magnetic force to improve the fidelity of kinesthetic guidance while mounting the magnet on a rotating platform enables multiple kinesthetic guidance methods. The magnetic force is rendered by controlling the position of the end effector. Results from psychophysical experiment demonstrated that kinesthetic feedback significantly influenced the handwriting kinematics in novel tasks.

As for future work, we plan to develop other haptic guidance methods such as providing disturbance vibration feedback (which is shown to be effective for maintaining attention while handwriting [9]). Moreover, we would like to utilize the developed platform to study the effects of kinesthetic feedback in handwriting learning and rehabilitation. Finally, we intend to develop and evaluate software algorithms to convert the current system into a surface haptic interface by rendering haptic textures.

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References

[1] S. Wollscheid, J. Sjaastad, and C. Tømte, "The impact of digital devices vs. pen (cil) and paper on primary school students' writing skills–a research review," *Computers & Education*, vol. 95, pp. 19–35, 2016.

[2] N. Girard, D. Simonnet, and E. Anquetil, "Intuiscript a new digital notebook for learning writing in elementary schools: 1st observations," 2017.

[3] Q. Yu, B. K. Chau, B. Y. Lam, A. W. Wong, J. Peng, and C. C. Chan, "Neural processes of proactive and reactive controls modulated by motor-skill experiences," *Frontiers in human neuroscience*, vol. 13, 2019.

[4] J. Danna and J.-L. Velay, "Basic and supplementary sensory feedback in handwriting," *Frontiers in psychology*, vol. 6, p. 169, 2015.

[5] D. Alamargot and M.-F. Morin, "Does handwriting on a tablet screen affect students' graphomotor execution? a comparison between grades two and nine," *Human movement science*, vol. 44, pp. 32–41, 2015.

[6] M. M. Patchan and C. S. Puranik, "Using tablet computers to teach preschool children to write letters: Exploring the impact of extrinsic and intrinsic feedback," *Computers & Education*, vol. 102, pp. 128–137, 2016.

[7] J. Guilbert, D. Alamargot, and M.-F. Morin, "Handwriting on a tablet screen: role of visual and proprioceptive feedback in the control of movement by children and adults," *Human movement science*, vol. 65, pp. 30–41, 2019.

[8] C. Jolly, R. Palluel-Germain, and E. Gentaz, "Evaluation of a tactile training for handwriting acquisition in french kindergarten children: A pilot study," *Kindergartens: Teaching mthods, expectations and current challenges*, pp. 161–176, 2013.

[9] W. Park, G. Korres, T. Moonesinghe, and M. Eid, "Investigating haptic guidance methods for teaching children handwriting skills," *IEEE transactions on haptics*, 2019.

[10] A. Withana, M. Kondo, Y. Makino, G. Kakehi, M. Sugimoto, and M. Inami, "Impact: Immersive haptic stylus to enable direct touch and manipulation for surface computing," *Computers in Entertainment (CIE)*, vol. 8, no. 2, p. 9, 2010.

[11] Y. Cho, A. Bianchi, N. Marquardt, and N. Bianchi-Berthouze, "Realpen: Providing realism in handwriting tasks on touch surfaces using auditory-tactile feedback," in *Proceedings of the 29th Annual Symposium on User Interface Software and Technology*. ACM, 2016, pp. 195–205.

[12] O. Portillo, C. A. Avizzano, M. Raspolli, and M. Bergamasco, "Haptic desktop for assisted handwriting and drawing," in *RO-MAN 2005. IEEE International Workshop on Robot and Human Interactive Communication, 2005.* IEEE, 2005, pp. 512–517.

[13] X.-D. Yang, W. F. Bischof, and P. Boulanger, "Validating the performance of haptic motor skill training," in *2008 Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*. IEEE, 2008, pp. 129–135.

[14] M.-C. Hepp-Reymond, V. Chakarov, J. Schulte-Mönting, F. Huethe, and R. Kristeva, "Role of proprioception and vision in handwriting," *Brain research bulletin*, vol. 79, no. 6, pp. 365–370, 2009.

[15] T. Yoshikawa and K. Henmi, "Human skill transfer using haptic virtual reality technology," in *Experimental Robotics VI*. Springer, 2000, pp. 351–360.

[16] C. L. Teo, E. Burdet, and H. Lim, "A robotic teacher of chinese handwriting," in *Proceedings 10th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. HAPTICS 2002*. IEEE, 2002, pp. 335–341.

[17] M. A. Eid, M. Mansour, A. H. El Saddik, and R. Iglesias, "A haptic multimedia handwriting learning system," in *Proceedings of the international workshop on Educational multimedia and multimedia education*. ACM, 2007, pp. 103–108.

[18] K. Karunanayaka, S. Siriwardana, E. R. Nakatsu, and P. Gopalakrishnakone, "Haptic mouse enabling near surface haptics in pointing interfaces," 2013.

[19] P. J. Berkelman, R. L. Hollis, and D. Baraff, "Interaction with a real time dynamic environment simulation using a magnetic levitation haptic interface device," in *Proceedings 1999 IEEE International Conference on Robotics and Automation (Cat. No. 99CH36288C)*, vol. 4. IEEE, 1999, pp. 3261–3266.

[20] C. R. Thornley, L. N. Pham, and J. J. Abbott, "Reconsidering six-degree-of-freedom magnetic actuation across scales," *IEEE Robotics and Automation Letters*, vol. 4, no. 3, pp. 2325–2332, 2019.

[21] Q. Tong, Z. Yuan, X. Liao, M. Zheng, T. Yuan, and J. Zhao, "Magnetic levitation haptic augmentation for virtual tissue stiffness perception," *IEEE Transactions on Visualization and Computer Graphics*, vol. 24, no. 12, pp. 3123–3136, 2017.

[22] S. Yoshida, H. Noma, and K. Hosaka, "Proactive desk ii: Development of a new multi-object haptic display using a linear induction motor," in *IEEE Virtual Reality Conference (VR 2006)*. IEEE, 2006, pp. 269–272.

[23] G. Pangaro, D. Maynes-Aminzade, and H. Ishii, "The actuated workbench: computer-controlled actuation in tabletop tangible interfaces," in *Proceedings of the 15th annual ACM symposium on User interface software and technology*. ACM, 2002, pp. 181–190.

[24] M. Weiss, C. Wacharamanotham, S. Voelker, and J. Borchers, "Fingerflux: near-surface haptic feedback on tabletops," in *Proceedings of the 24th annual ACM symposium on User interface software and technology*. ACM, 2011, pp. 615–620.

[25] J. Yamaoka and Y. Kakehi, "depend: augmented handwriting system using ferromagnetism of a ballpoint pen," in *Proceedings of the 26th annual ACM symposium on User interface software and technology*. ACM, 2013, pp. 203–210.

[26] T. Langerak, J. Zarate, V. Vechev, D. Panozzo, and O. Hilliges, "A demonstration on dynamic drawing guidance via electromagnetic haptic feedback," in *The Adjunct Publication of the 32nd Annual ACM Symposium on User Interface Software and Technology*. ACM, 2019, pp. 110–112.

[27] J. Bluteau, S. Coquillart, Y. Payan, and E. Gentaz, "Haptic guidance improves the visuo-manual tracking of trajectories," *PLoS One*, vol. 3, no. 3, p. e1775, 2008.

[28] A. Teranishi, G. Korres, W. Park, and M. Eid, "Combining full and partial haptic guidance improves handwriting skills development," *IEEE transactions on haptics*, vol. 11, no. 4, pp. 509–517, 2018.

[29] G. Lehmann, "Kappa sigma clipping," *Insight J*, 2006.