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Joel Chevrier

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A Low-Cost Grip Pen Sensing Tool to Detect Handwriting Disorders

Ana Phelippeau*
Learning Planet Institute
Paris, France
ana.phelippeau@cri-paris.org

Wim Poignon*
Léonard de Vinci Pôle Universitaire,
Research Center,
Learning Planet Institute,
Paris, France
wim.poignon@edu.devinci.fr

Adrien Husson
Learning Planet Institute
Paris, France
adrien.husson@external.cri-paris.org

Marc Teyssier
Léonard de Vinci Pôle Universitaire,
Research Center,
Paris La Défense, France
marc.teyssier@devinci.fr

Clément Duhart
Léonard de Vinci Pôle Universitaire,
Research Center,
Paris La Défense, France
clement.duhart@devinci.fr

Joël Chevrier
Université Grenoble-Alpes,
Grenoble, France
joel.chevrier@univ-grenoble-alpes.fr

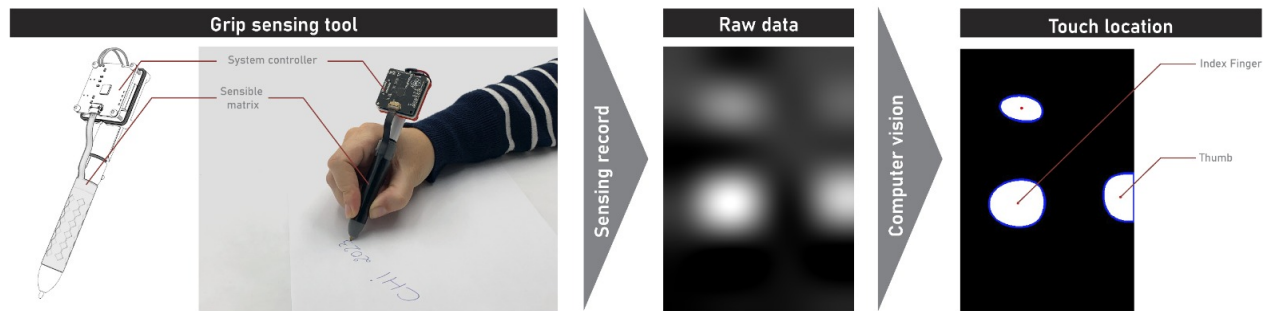


Figure 1: Overview of the grip pen sensing tool. *Left.* The hardware grip sensing tool is attached to a regular pen. A sensitive matrix is wrapped around the body of the pen, and data processing algorithms are performed to detect grasp posture.

ABSTRACT

Handwriting is a complex motor activity. Neurodevelopmental disorders, such as dysgraphia can lead to severe handwriting difficulties. These dysfunctions could be predicted by measuring the pen's motion, the pressure of the tip and the grip force while handwriting. Various hardware platforms have been proposed to sense pen movement. However, the grip force sensing is more challenging and often requires high-end sensing devices. In this paper, we propose a low-cost pen grip sensing tool to detect pressures and positions of fingers on the pen. It consists of a flexible, mutual-capacitive sensor rolled around the pen and connected to an inexpensive microcontroller. We provide initial tests of our grip sensing tool on multiple single-touch conditions. The results show a homogeneity over the flexible sensor and a linearity of the response with several

curvatures. Such novel device open new opportunities for neurodevelopmental disorders research and new possibilities for clinical purposes.

CCS CONCEPTS

• **Hardware** → *Tactile and hand-based interfaces*; • **Human-centered computing** → *Human computer interaction (HCI)*; • **Applied computing** → *Health care information systems*.

KEYWORDS

Flexible printed circuit, Sensitive matrix, Multi-point input, Grip force, Digital pen, Handwriting disorders

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1 INTRODUCTION

Handwriting is one of the crucial functional daily activities required of school-aged children for their academic success [19]. However an estimated 5-10% of children fail to write correctly [45, 47] and face

*Both authors contributed equally to this research.

developmental dysgraphia [28]. Handwriting is a complex motor activity.

The movement of writing is one of the most rapid of all human movements [10] and it requires the coordinated activity of 43 muscles and joints of the arm, hand, and fingers to produce letters [34]. Measurements and analysis of pen movement and finger grip force are valuable and important descriptors of individual impairment characteristics [24]. Holding or grasping a pen requires strong fingers and hand muscle grip, and overpressure affects handwriting movement fluidity. Grip is defined as the forces exerted by the thumb and fingers on the barrel of the pen [46]. Thus, handwriting performance is conditioned by the level of force exerted by the fingers on the pen [11].

Various dedicated hardware platforms have been used to sense the motion of a pen. These platforms traditionally rely on external precise 3D location tracking devices (IR, Optitrack [31, 53]) or motion sensing through IMU attached to a pen [38, 40, 51, 52]. The pressure exerted on the tip of the pen is higher for children with dysgraphia [32, 43], and is a crucial parameter that has also been measured with low-cost hardware interfaces.

Only few tools have been proposed to measure the grip force. They are often expensive, heavy and bulky items that require to be wired [4], to be fixed on the wrist of the writer [4], numerical tablets or constrain the grip posture [26]. Moreover, they are not similar to the pen children use on a daily basis. Bulky interfaces impair natural manipulation and high cost may restrict the deployment at a large scale or the reproduction in a DIY setting.

We have developed an interactive pen that can sense both motion, pressure of the tip of the pen and grip force of handwriting tasks. In this paper we specifically present our 2D flexible sensor wrapped around the pen and its performances in measuring the grip force. The overall system is composed of a micro-controller circuit placed on a traditional Bic 4 color ball-point pen. The circuits are composed of an inertial motion unit (IMU), capable of sensing motion of the pen and a multi-touch sensing circuit, capable of sensing finger grip. The multi-touch sensing surface is wrapped around the barrel of the pen, and allows to measure the precise pressure and location of the fingers when holding the pen. We also provide the pipeline for data acquisition, treatment and management and give initial results of the grip sensor characterisation.

This tool allows to gather data on the grip force in order to have a better understanding of the handwriting learning process. This tool is a low-cost and DIY-friendly alternative to help with the diagnosis and rehabilitation of developmental dysgraphia in children. While the system is composed of both an IMU, a tip force sensor, and a sensing surface, this paper only focuses on the presentation and implementation of the grip system, often overlooked in the current literature. Our proposed system integrated in an existing Bic 4 colors ballpoint pen makes the pen suitable to children manipulation abilities and will be easily deployed in a classrooms.

2 BACKGROUND AND RELATED WORKS

2.1 Grip force in handwriting tasks

The grip force has a clear impact on handwriting performance but also on muscular fatigue and pain for the writer. The writer encodes information on the physical properties of the pen (shape, texture,

weight) to adequately set the grip force in order to prevent the pen from slipping out of their fingers [11]. Children with dysgraphia have a significantly lower tripod-pinch strength and use lower grip force variability compared to proficient writers [17, 30]. This is associated with a significant deterioration of the handwriting process, i.e., the graphomotor gesture and product that is the written trace measure [18]. Alaniz *et al.* found that grip strength is also correlated with pencil control and handwriting legibility [2]. During long handwriting tasks, grip force tends to increase over time [28]. Overpressure leads to poor proprioceptive-kinesthetic awareness that influences both the pencil grip and the force applied to the writing utensils [18]. Increasing the grip stiffness and the forces on the pen could lead to a decrease of the proprioceptive feedback from the fingertips as a consequence of the overpressure exerted on the tactile receptors [11]. Besides, adults with writer's cramp apply an exaggerated force on the barrel of the pen, leading to a degraded writing performance in comparison to those of healthy subjects [24]. The location of the fingers is also an important parameter that needs to be detected. Thumb position is related with the grip force in 9 years-old children [46]. Mean grip force is stronger for the lateral thumb position than for the dynamic thumb position on the barrel of the pen [46]. Measuring the grip force is thus crucial for handwriting impairment diagnosis and rehabilitation, and tools have been proposed in the literature.

2.2 Grip pens

2.2.1 Grip pens. Several digital pens that measure grip force were developed over the past years. Chau *et al.* [7] developed a novel instrument composed of a pressure-sensitive liquid crystal display (LCD) writing surface, a desktop computer, and an instrumented writing utensil. The latter consists of a regular pen instrumented with a pressure sensor array on its barrel. The Kinetic Pen is described in Hooke *et al.* [25]. The pen is equipped with four force sensors located in the pen's body, providing a four contact-point writing grip: thumb, index finger, middle finger, and webbing between the thumb and index finger. Finally, the Force Acquisition Pen (FAP) was proposed by Hsu *et al.* [26]. The lower barrel of the FAP contains three thin beam force sensors, for thumb, index and middle finger.

2.2.2 Grip pens associated with tablets. Researchers have proposed grip pens associated with graphical tablets to measure writing kinematics. The grip pen developed by Chau *et al.* [7] was adapted and used in several other studies, such as Falk *et al.* and Schweltnus *et al.* [18, 46]. To measure the force exerted by the fingers against the pen, Hermsdorfer *et al.* [24] used a force sensor matrix, wrapped and glued around the stylus of a graphic tablet. However, the axial force sensor is not designed for high forces and the pen pressure produced by patients with pathological force increase may exceed the measurement range. Bashir *et al.* [3] designed the enhanced biometric pen (BiSP). The grip forces are monitored by a piezoelectric film wrapped around a ballpoint pen. The finger grip sensor is mounted beneath the rubber cover of the tablet's pen device.

2.2.3 Grip pen using an IMU. Song *et al.*, 2011 [48] used a Wacom Intuos/Cintiq grip pen augmented with a custom capacitive sensor. A plastic cylindrical enclosure was wrapped around the pen to place

a flexible matrix of capacitive-sensing electrodes that track the image of the user's hand. This apparatus appears to be sufficient to sense many of the typical hand contacts while using the pen. A PCB, located at the rear end of the pen, controls the sensor, captures raw capacitance values, and communicates these to a computer via USB.

These devices provides a limited measurement quality due to various biases induced by their design – no realistic writing surfaces, measurement range constraints, bulky hands-on devices. Hence, our motivation has been the development of an integrated and adaptive high sensitive and high resolution builtin grip pen, relying on flexible touch sensing.

2.3 Flexible Touch Sensing

Researchers have investigating capacitive touch screens in the 1970's [5]. Capacitance sensors identify a touch by detecting a capacitance variation on an electrode cross-section. Compared to the self-capacitance, the mutual principle counters the problem of ghost touches [9] in multi-finger usage like grip analysis. Capacitive sensors are composed of transmit (TX) and receive (RX) electrodes to form a grid array of conductive wires. Each capacitive coupling of RX/TX electrodes, separated by an insulator, creates a variable capacitor (C_M). In recent years, studies have explored flexible capacitive touch sensing on soft surfaces [42]. They can be applied inside textiles [13, 23, 41], on thin printed paper [22, 27, 37], or on silicone [12, 33, 39, 49, 50]. The explorations of multi-touch input lead to new opportunities in HCI. Nittala et al. explored skin-based touch sensing to enhance direct, subtle, and expressive interaction [35]. Gong et al. present a versatile sensing technique to support multi-modal flexible surface interaction [22]. Aigner et al. demonstrated interactive garments by manufacturing a textile mutual capacitive sensor [1].

3 GRIP PEN

In this section, we describe our grip pen and its implementation. The device is designed as a low-cost, non-invasive and stand-alone device. It relies on a commercially available ball-point pen, augmented with hardware sensing circuits. This pen is divided into 2 different part, as shown in Fig. 1. The top part part that holds the MCUs and tip force sensor and the bottom part, dedicated to sense grip.

3.1 Pen System Overview and Implementation

3.1.1 Pen Body. The pen body is composed of a Bic 4-color ball-point Pen. This pen is 14.5cm long with a diameter of 8.3cm. The weight is 11 grams, and the price 3.22 EUR (3.24 USD). This pen is very easy to handle and well known from children in schools. Pencil for children in kindergarden are recommended to have a 10mm diameter [6] and the regular pencil diameter is around 7.5mm for middle school age children and adults [6, 36]. We 3D printed a part similar to the Bic 4-color ballpoint Pen default enclosure, in a grey photopolymer resin (RS-F2-GPGR-04). The printed cylinder facilitates the placement of a battery within and has a clear surface to fix our sensitive matrix with a double sided tape.

3.1.2 System Controller. The sensing relies on Movuino platform (<http://www.movuino.com>) fixed on the top of the pen, an open-source development platform, dedicated to sensing motion and gestures. The electronic board is based on an ESP32 microcontroller, hence containing a bluetooth antenna and WIFI, a battery management system, a neopixel LED and a embedded memory. Pins are exposed to connect custom-based shields. The total cost of a Movuino is 20 USD.

3.1.3 Motion and tip force sensing. The Movuino platform is equipped with the 9-axis motion tracking MPU 9250 by InvenSense. The tip force sensor we have developed is a resistive sensor placed at the upper-base of the pen's lead and linked to the Movuino thanks to an additional PCB. This motion and tip force sensing are part of the overall apparatus but will not be discussed further in this paper, as we focus on the grip force measurement system.

3.2 Capacitance Sensing Circuit

For this work, we developed a shield based on the MuCa board [49], allowing sensing mutual-capacitance. The board features a single-chip capacitive touch panel controller FT5316DME MCU by FocalTech. The capacitive touch panel controller works by a sensor driver that sends an AC signal to each transmitter Tx electrode one at a time. The Analog Front-End (AFE) measures the capacitance at each Rx/TX intersection. The analog values are converted to digital by an Electronic Analog Computer (EAC) with a low-power internal oscillator. A high-speed Digital Signal Processor (DSP) runs signal processing algorithms on a MCU to process the capacitance data and to detect the touches reliably. The raw data of all intersections is read at a 50Hz rate. The built-in hardware gain can also be adjusted to limit noise and control the measurement range. Communication protocol software is also implemented on the MCU to exchange data with the host processor via I2C interface. The system work on a 3.3V power supply and is low-power (0.05mAh/per scan).

3.3 Capacitance Sensing Layout and Fabrication

3.3.1 Sensitive matrix requirements. The geometrical layout of the electrodes and the materials affect the accuracy and noise sensitivity of mutual capacitive sensors [29, 35]. The sensitive matrix requires a suitable flexibility and appropriate dimensions to surround perfectly the entire pen. After being rolled around the grip pen, the capacitance sensing layout must be connected to the sensing circuit to communicate with. The pad layout requires a maximum sensitivity, a good noise tolerance, and a minimum touch latency to track properly the fingertips.

3.3.2 Materials and fabrication. We selected a flexible printed circuit board (FPCB) (manufacturer PCBWay) to fabricate the mutual capacitive sensor. Some results show that two-layer design (TLD) are highly appropriate for implementation on a flexible PCB as it simplifies the routing for the RX/TX electrodes [8]. On our FPCB, two layers of conductors (on Fig. 2 (a-d), red for the top-layer and the green the bottom-layer) are striped with the RX/TX electrodes and insulated by layers of dielectric material. The conductor is made of copper with a thickness of $18\mu\text{m}$ ($0.5\Omega/\square$). Polyimide (PI) material is prevalently used for the insulator with a thickness of

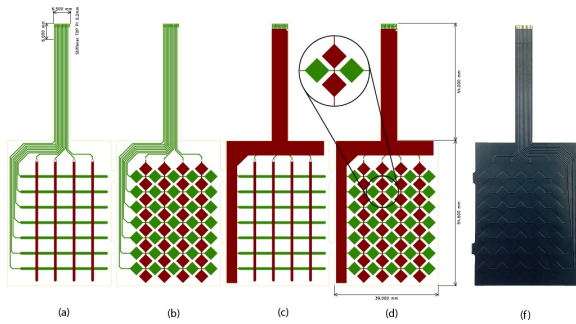


Figure 2: Schema of different pattern designs of the sensitive matrix. (a) and (b) show the line and diamond pattern without a shielding layer. (c) and (d) figure the same designs with no shielding layer. (f) represents our manufactured sensitive matrix.

10 – 20 μm because of its good dielectric properties and low coefficient of thermal expansion (CTE). The overall sensor measures 39 x 98.6mm with a thickness of $\sim 0.1\text{mm}$ for a total price of 12.5 EUR (13.5 USD) per unit (without shipping fees). A 2mm stiffener has been added on top to connect properly to the sensing circuit. The total cost can be reduced to $\sim 2\text{\$}$ per unit once mass-manufactured.

3.3.3 Design. Various matrix designs have been explored to sense mutual-capacitance. The diamond pattern [8] is one of the most commonly used today, because it maximizes the exposure of sensor electrodes to a touch. The design consists of diamonds interconnected with a narrow neck sections as shown in Fig. 2. Two main parameters relate to this pattern, namely pitch and gap. Typical dimensions have been reported by Microchip [8]: 6mm for the row/column pitch and 0.5 mm gap between them. The mutual capacitance sensor is very thin and gripped by fingers, the human capacitance will manifest as parasitic noise in the sensor readings, especially when the fingers touch the link wires between the sensor and the touch panel controller. Adding a shield on top of connections will counter this problem [35]. It has to be connected to the chassis ground of the electronic circuit to create a fix potential.

3.4 Signal processing and touch detection

The signal processing pipeline is composed of two processes. The hardware calibration will increase the sensitivity of the sensitive matrix and the touch detection is done thanks to computer vision.

3.4.1 Hardware calibration. We initialize a calibration matrix filled with the mean of the 20 first lines for each RX/TX electrode. Once the calibration is done, we subtract the baseline matrix to each new reading data to reduce the background noise. In addition, changing the built-in hardware gain changes the signal-to-noise ratio (SNR) in line with the formula (1). We measured the signal of one intersection with and without contact force three times for multiple hardware gains (1-30 levels by step of 5). The optimal gain was set at 15 for a SNR of 54dB.

$$SNR_{dB} = 20 \log \left(\frac{|\overline{x}_{nc} - \overline{x}_c|}{\sigma_{nc}} \right) \quad (1)$$

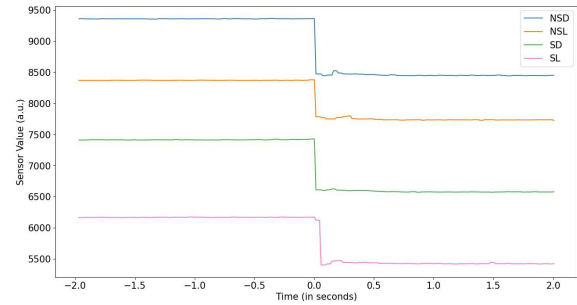


Figure 3: Sensor response (arbitrary unit) with no touch (from -2s to 0) and with touch contact (from 0 to 2s) of different pattern designs. Blue=no shield with diamond pattern (NSD); yellow=no shield with line pattern (NSL); green=shield with diamond pattern(SD); pink=shield with line pattern (SL).

where \overline{x}_{nc} and \overline{x}_c are respectively the average values of no contact and contact, σ_{nc} stands for standard deviation.

3.4.2 Computer vision. OpenCV algorithms are used to treat the sensing output and detect the touch areas. After calibrating the system, the incoming array is transformed into a matrix, which serves as a baseline for a 2D image. Each intersection value represents a grayscale pixel. The image (7x4 pixels) is then resized by a factor of 100 using the Lanczos-4 interpolation (Fig. 1 middle). We apply a 55% threshold to the image following previous literature [50] to find the contour, thus locating the fingers (Fig. 1 right).

4 PERFORMANCE OF THE MULTI-POINT SENSITIVE MATRIX

This section describes the initial characterization of the sensitive matrix. The studies presented in this paper were conducted on the same experimental apparatus. We built a custom apparatus that was holding a conductive stylus in a vertical upright position. The role of this stylus was to simulate a finger. The sensitive matrix measured was then placed underneath the conductive stylus. The tip was placed $\sim 2\text{mm}$ above the sensitive matrix. We then applied a vertical pressure force on the stylus until it made a contact with the measured sample. Placing a baseline weight (113g) on top of the conductive pen stylus simulates a regular touch. As we used the same apparatus and the same weight across all experiments, the pressure applied on the sensitive matrix was equivalent for all experiments.

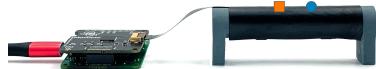
Sensor response to pattern designs. We first conducted a mechanical characterization to evaluate how the sensor reacts to the conductive stylus. We recorded the incoming data of a single intersection for 4 seconds at a rate of 77Hz (308 responses in 4 seconds). During the first half-time (0 to 2 seconds), no force is applied to the sensor. Then, a weight (113g) is placed on top to push the stylus down, enabling a touch (from 2 to 4 seconds). The experiment is repeated for each pattern design (diamond vs. line and shield vs. no-shield). The results are presented in Fig. 3. The sensors with a shield have a lower value thus decreasing the capacitance of the intersection.

Meanwhile, the diamond pattern covers a larger area and increases the sensor value.

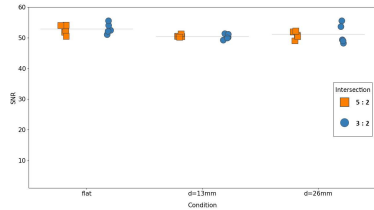
Linearity of the response with several curvatures of the flexible sensor. We evaluated the effect of PCB flexion on sensing, to assess the feasibility and the sensor response to a wrapping around the body of the pen. We investigated how the different curvature conditions affect the mechanical response of touch input. We studied three different conditions. First, the flat condition, with the sensor placed on the table. Second, a curvature with a diameter of 26mm was tested by rolling up the sensor around a half-cylinder (Fig. 4a). We repeated the procedure with a 13mm diameter cylinder (Fig. 4b).



(a) Half-cylinder (∅13mm)



(b) Cylinder (∅26mm)



(c) SNR for the different curvatures : flat, (a) and (b)

Figure 4: Flexible sensitive matrix positioned in two different bending apparatus: 13mm (a) and 26mm (b) diameter cylinders. Signal-to-noise ratio (c) of the three conditions (flat, ∅13mm and ∅26mm). Orange squares and blue dots shows two different measurements. The SNR is shown beyond 50 whatever conditions of curvature.

We calculated the SNR of two cross-sections for each condition, which we plotted in Fig. 4c. We expect to maintain consistency in the different sensor response measurements at a given intersection despite a curvature in our flexible sensor. We observed a decrease of the SNR by curving the flexible PCB of about $\sim 5\%$. This difference does not impact our use case significantly.

Influence of a shielding layer on the sensor. We evaluated the influence of a conductive shield by analyzing the sensor response in four conditions: applying (or not) a force on a specific intersection with (and without) touching the shielding layer. For each experiment,

we calculated the average of the raw capacitance data on a seven-second record. We observed no abnormal changes while touching (6694 arbitrary unit (au.)) or not (6614 au.) the shielding layer in the condition of pressed stylus. The values decrease from 7420 to 6700 au. when the pen stylus applies a force on an intersection. The results predict that the finger response keeps its value regardless whether the shielding area is touched.

Single-touch homogeneity over the sensor. We evaluate the homogeneity of capacitance values over the sensor for a single-touch. We read the sensor response of the same intersection continuously ($rx = 3$; $tx = 2$). Using the experimental apparatus, each intersections is tested with a touch contact using the capacitive stylus, one-by-one. Each contact lasted 4 seconds. We expected that the response remains the same despite the noise created by touching the other intersections. The Figure 5 represents the average response of the intersection during a 4 seconds contact on each cross-section. The results shows that the responses remain homogeneous over the sensitive matrix. Computer vision algorithms could guarantees a reliable touch detection over the sensor.

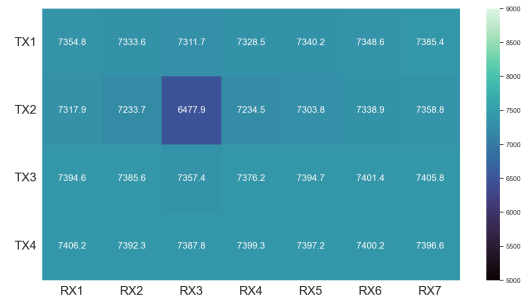


Figure 5: Mean of the sensor response (arbitrary unit) of a single intersection ($rx = 3$, $tx = 2$) while every intersection is touched separately one-by-one.

5 DISCUSSION AND CONCLUSION

In this paper we present the grip pen and the multi-point sensible matrix which allows to measure grip force of the fingers on the barrel of the pen while handwriting. Our technical experimentation presented previously shows consistent results without particular manufacturing attention and an easy integration at low-cost within commercial pens. We expect that such device will be easily built by clinical practitioner thanks to our DIY kit.

We have underlined the importance of measuring grip force which complements measurements of pen motion and forces on the pen tip. Based on this analysis, we have then built a sensitive matrix and showed how it can be integrated in a pen. We have further explored its performance, namely sensitivity, signal to noise ratio and touch latency, and shown that they fulfill the requirements. The pen design enables uses without other external equipment in medical and paramedical practices, schools or retirement homes, thus allowing the use of this tool and data collection in natural environments of children or elderly people.

5.1 Use cases

We have identified two use cases that we would like to explore in a future work. First, to our knowledge, such a sensor does not exist associated with regular pen, and we anticipate that this sensitive matrix might have impact both for clinical and research purposes. Measuring the grip pressure and location is important to characterize both the quality (e.g., legibility) and speed of handwriting. Thus, this sensor will provide new insights concerning the development of handwriting gesture and its impairments. It can contribute to develop new pre-diagnosis and diagnosis tools (e.g., developmental dysgraphia). It would complement existing tests and methods, as it is faster to use and easier to deploy at large scales. This tool can also aim to be a rehabilitation tool. Besides, numerous studies [14–16, 20, 21, 44] have shown that early markers of Alzheimer's or Parkinson's disease can be diagnosed through manual handwriting impairment. Excessive pressure is one of them. This tool might help develop early, non-invasive, rapid and inexpensive diagnostic tests to Parkinson and Alzheimer's diseases. Secondly, this sensitive matrix can be used in schools, for educational purposes. As our device is meant to be adjustable, user interactive output features can easily be added. We envision adding lights or sounds to the device so it can help children to learn how to write more easily. The light can turn red or a specific sound can be played if children apply too much pressure on the barrel of the pen.

5.2 Beyond the Single Finger Contact

The use of single touch allows us to have a precise location and pressure of the finger on the barrel of the pen with an SNR above 50. We tested to touch the sensitive matrix with multiple fingers, and the system is capable to detect the touch area but adds some noise in the data. Further data analysis and noise-cancellation algorithms needs to be implemented to ensure a robust reading. In addition, it must be noted that discrimination of fingers touching the pen, e.g., which contact is due to thumb, index, or middle finger is still an open question. These improvements will be performed with software implementation and revised version of hardware ergonomics. To date, the sensitive matrix is rolled over the body of the pen. We hope to obtain in a revised version of the prototype an integrated solution, where the sensor is not apparent and electronics parts are hidden. This device being intended to be used by children and elderly people, their safety and security must be a primary concern. To conclude we propose a grip pen tool to measure grip force on a pen for educational, clinical and research purposes. We believe it is now ready to be used and produced.

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