

Article

Sensorised Low-Cost Pencils for Developing Countries: A Quantitative Analysis of Handwriting Learning Progress in Children with/without Disabilities from a Sustainable Perspective

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Abstract: Learning to write is a demanding endeavour that requires a combination of linguistic, motor and cognitive skills. Some children suffer from delay or inability to acquire those skills, which often hampers their performance at school and brings about serious consequences for self-esteem, personal expectations and social relationships. The situation worsens in developing countries, due to the lack of resources and specialised personnel. With this background, this paper describes an experiment with a newly-developed sensorised pencil with triangular prism shape, which is shown to yield substantial improvements in children with/without special education needs. A team of experts in the areas of speech therapy, occupational therapy, educational psychology, physiotherapy and pedagogy have expressed very positive opinions about the sensorised pencil and the accompanying software for the acquisition and analysis of quantitative data about handwriting. Furthermore, the device stands out for its low cost in comparison with similar developments, which is a key factor to aid children from low-income families. This fact is explained with a success story of manufacturing and delivering sensorised pencils in the Ecuadorian province of Azuay, framed in a multi-layer sustainable development perspective based on collaboration of several institutions and individuals.

Keywords: handwriting development; sensorised pencils; third-grade and fourth-grade children; special education needs; sustainable technology development

1. Introduction

Writing is an essential part of language development that children must acquire in order to advance their education. Learning it is a demanding task, as it requires the consolidation of linguistic, motor and cognitive skills. The development of oral language and the knowledge of letters are some of the key linguistic skills. Adding to those, the child must be able to control the muscles and nerves to make intentional movements and eye-hand coordination. Ultimately, it is necessary for the child to recognise that he/she can express and specify her thoughts through drawing or writing. All these skills develop progressively and simultaneously as the child grows.

In the specialised literature two concepts are usually distinguished [1]: handwriting refers to the mechanical ability to write, whereas *writing* is the ability to produce structured text. There is evidence about the close connection between the two concepts, more specifically, between the ability

to write legible text and to do it in an organised way and in reasonable time. Most children can acquire the necessary skills in handwriting, thus managing to handle writing with adequate competence. However, there are children who are not capable of developing proper handwriting skills, which leads to dysgraphia, often evidenced through low speed of writing and illegibility of the letters drawn. According to the World Health Organisation (WHO), dysgraphia has a prevalence that varies between 10% and 30% in school-age children [2], and numerous studies classify it as one of the main problems that limit learning in school [3]. Thus, children who cannot write adequately often have difficulty keeping up with the required pace in class, especially when copying from the blackboard. Besides, the WHO considers that inadequate handwriting can affect many areas of life, causing a loss of self-esteem, with serious consequences for personal expectations and even social relationships.

There is extensive evidence that the better the pencil is grasped, the greater the writing speed and readability will be [4–6]. Likewise, it has been shown that incorrect grip can be the origin of inadequate speed and readability, persisting in professional settings during adult life [7]. For decades, there has been debate about the most convenient types of grip. From among the most common ones (see Figure 1), the dynamic tripod has been traditionally promoted as the most suitable in many educational systems around the world, for inducing the lowest pressure, tension and fatigue [8] and for ensuring a more relaxing and physiologically superior posture, thanks to the use of the thumb, index and middle fingers [9]. Long ago, however, Ziviani and Elkins [10] studied the impact of the types of grip after a 10-min copy task, designed to induce muscle fatigue, and found that the dynamic tripod offered no advantage over the lateral tripod, the dynamic quadrupod and the lateral quadrupod, neither with children showing normal development nor with others who suffered from lags to different extents. Along the same lines, Koziatek and Powell [11] studied the effect of different types of grip on writing speed and readability, concluding that the lateral quadrupod and four-finger grips are as functional as the dynamic tripod, the lateral tripod and the dynamic quadrupod.

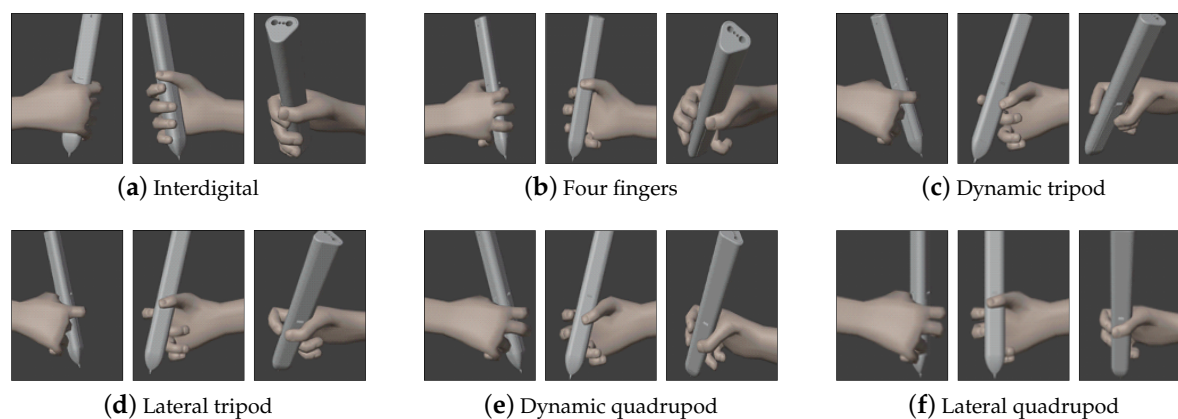


Figure 1. Types of pencil grasps.

Recently, advances in the area of electronics have allowed the development of sensorised pencils and styluses, with which a plethora of parameters can be measured in relation to the grip and the speed and readability of the writing: pressure at different heights of the pencil or stylus, speed and directionality of the strokes, inclination, etc. This has extended the debate to study the types of grip in combination with aspects of the design of the writing instruments, revisiting old studies which suggested that the geometry of the pencil does not have a significant influence [12,13].

In this article, we present a study with a newly-developed sensorised pencil with triangular prism shape (like the one shown in the sketches of Figure 1), in comparison to the common cylindrical pencils. The triangular shape was chosen to subtly promote a shift towards the dynamic tripod grip, due to the advantages proved by Azzam [14] in his experiments with children affected by hemiplegia. (Azzam found the dynamic tripod universally valid to ease the development of coordinated fine movements. In fact, he used it in a method to rehabilitate the hand arch, which requires the stabilisation

of the little and ring fingers, produced by the flexed position towards the palm to support the distal transverse arch and the third finger during the pencil grip). The entire design was driven by the aim of attaining an affordable device, in order to bring the technologically-enhanced therapies closer to the reality of developing countries, such as Ecuador, in which cost is a determining factor for many families.

Our experiment was conducted over a period of 4 months, involving children from Ecuadorian low-income families. The children were aged 7 to 10, with and without special education needs (hereafter, SEN) associated or not with some form of disability. The results show that the triangular prism shape helps to attain better grip and writing quality, especially when used during early stages of skill development, and in the cases of children with SEN. The pencil, together with the accompanying system for acquisition and analysis of quantitative data about handwriting performance, also gained acceptance among the experts who collaborated and supervised the experiment, coming from the areas of speech therapy, occupational therapy, educational psychology, physiotherapy and pedagogy. On the other hand, in this paper we equally describe the schematic proposal put to test to design, make and deliver 50 sensorised pencils to children from low-income families assisting to a public school. To this aim, our proposal considers a multi-layer sustainable perspective based on collaboration of several institutions and individuals.

The article is organised as follows. Section 2 contains a review of related works with technology-enhanced pencils and styluses. Section 3 presents the design of our experiment, followed by the results and discussion in Section 4. Section 5 describes the success story of manufacturing and delivering sensorised pencils in the Ecuadorian province of Azuay, framed in a multi-layer sustainable development perspective based on collaboration of several institutions and individuals. Section 6 provides a summary of conclusions and the motivation for future work following our findings.

2. Related Work

Rosenblum et al. [15] led one of the earliest studies to measure and characterise the biomechanical processes of handwriting, with the aid of an electronic tablet. Ergonomic factors, measures of handwriting quality and efficiency were rated using the Hebrew Handwriting Evaluation criteria, finding that all the parameters significantly differentiated between the study groups of proficient and non-proficient writers. Shortly after that, Hooke et al. [16] presented their Kinetic Pen, capable of measuring the six-component force and torque that each of four individual contacts applied to the pen during writing. This type of tools allowed handwriting studies to be expanded from two-dimensional pen-tip kinematics to three-dimensional dynamics at each contact point between the hand and the writing instrument. Over the last decade, the literature has gathered a number of studies using pencils and styluses equipped with accelerometers, pressure sensors and other devices to gain further insight into the handwriting processes as people's relationship with handwriting evolves in the digital era. A survey of the types of sensors, as well as measurement and estimation techniques, can be found in [17].

The following are some notable works that used the measurements to derive recommendations to improve the learning of handwriting skills:

- Falk et al. [18] performed a comprehensive study of the grip forces and how they vary over time during a handwriting task. Force variability measures were computed and tested as correlates of handwriting legibility, form and strokes, showing that grip force variability correlates strongly with handwriting quality, in particular for students classified as non-proficient writers. Static grip force patterns were shown to result in poor handwriting quality and in greater variation in handwriting stroke durations.
- Gupta et al. [19] created a low-cost device called the S-Pencil to continuously monitor the children's grip and writing activity. The device is coupled to a data collection system, which feeds machine learning modules that classify the results of exercises recommended by a mobile app.

- Farris et al. [20] presented a study of the relationship between muscle tone, legibility and consistency of writing with reference to grips, finding that dynamic grips are beneficial for right-handed children (not so much for left-handed ones) to develop fine movements, whereas lateral grips were better to improve gross muscle activation.
- Whittaker et al. [21] presented several iterations in the design of a stylus for tablets that would facilitate its use by children aged 4 to 7, and that at the same time would allow them to develop fine-motor skills. They initially discarded the triangular prism shape for technical difficulties to mold it and to fit the required sensors inside. Yet, they added finger wedges and ridges in order to replicate the effect of having a triangular grip.

It is interesting to mention various patents that present add-ons for electronic pencils and styluses to facilitate the acquisition of writing skills, most often focused on the grip:

- Provda and Provda [22] presented a grip that promotes thumb opposition for hand tools that have elongated handles, including writing instruments. The pinch grasp area can accommodate a distal end of an index finger and a distal end of a thumb of a user, so that a tip of the thumb is opposed to a tip of the index finger in a pinch grasp.
- Pincus et al. [23] described a pen/pencil grip with a head section, a middle section and a tail section forming a continuous and smoothly connected body. Positioned on the grip are placement recesses and grooves to accommodate the thumb, index finger, middle finger, ring finger, little finger, and thenar eminence of a hand. The grip also includes a channel to receive the shaft of a pen/pencil. The structure is designed to reduce fatigue when writing, fostering a tripod grip without putting pressure on the middle, ring and small fingers.
- Marin and Marin [24] presented methods and systems for facilitating handwriting for individuals who require assistance with their fine motor skills and pinch strength due to various conditions or injuries, such as loss of strength in the main muscles and ligaments used for writing. The solutions include a writing instrument with variable weights and diameters, that may be adjusted in order of succession based on improved or worsened fine motor skills.
- Walden [25] presents a cone-shaped gripping aid that features various methods to assist adults and children in gaining the ability to relieve finger pressure upon a writing implement, to improve hand steadiness, and to attain a firmer and improved grasp.
- Finally, Forester and Forester [26] proposed a system and method for training correct positioning and pressure of fingers on writing instruments, thanks to embedded force and tilt sensors.

From our analysis of the state-of-the-art in the area of sensorised pencils/styluses and technological aids to handwriting acquisition, we have estimated the costs incurred to manufacture (or reproduce or reverse-engineer) one fully-functional device in Ecuador, where (i) there is no large-scale demand and no industrial infrastructure to streamline many processes, (ii) some technologies, such as multi-layer Printed Circuit Board manufacturing are not available, and (iii) many imports are severely charged with customs duties. We also estimated the time required to produce a fully-functional device, involving one hardware engineer and one software engineer. The estimates are shown in Table 1.

We have compiled a list of relevant contributions to collect handwriting graphomotor data. We have made a projection of the time needed to develop the model described in each research. Similarly, for each contribution, we estimated the costs of obtaining the materials in Ecuador. As can be seen, the fabrication costs are high in Ecuador, as in other developing countries in Latin America. Below we present some critical considerations of “reproducing” these technological solutions:

Table 1. Estimates of fabrication/acquisition costs (USD) for devices and services comparable to our sensorised triangular prism pencil.

Reference	Highlights	Cost (USD)	Fabrication Time (Days)
Crane et al. [27]	Sensitivity analysis of pressures in the three axes when writing; connection by cable to a computer.	490	4
Diddens et al. [28]	Signature recognition by pressure sensitivity matrix using finite elements for characterisation.	630	5
Hooke et al. [16]	Three-dimensional measurements of pressure, time, writing speed, fingerprints; signature recognition by recording the sound of the writing.	700	5
Shimizu et al. [29]	Measurements of pressure in all axes and angle of inclination of the pen	950	8
Chau et al. [30]	Touch screen digitiser with pressure gauge; grip system equipped with 32 pressure sensors.	850	–
Hooke et al. [16]	Three-dimensional force analysis that allows quantifying the torques of the finger joints when trying to write.	800	6
Kamel et al. [31]	A glove that measures a matrix of distributed energy parameters by means of the finger flexions.	880	7
Wang et al. [32]	Reconstruction of trajectories using a sensorised pen that contains a triaxial accelerometer and two gyroscopes.	750	5
Calusdian et al. [33]	Generation of traces detected through accelerometers and magnetometers after an initialisation in space.	700	6
Malik et al. [34]	A camera taking data through Gaussian mixture models; detection of signature forgery.	650	5
Bashir et al. [35]	Commercial digitising tablet and stylus, plus digital grip pressure sensors.	850	–
Djioua et al. [36]	A kinematic study of writing using PDA and longitudinal sigma.	1300	5
Rosenblum et al. [37]	A digitising tool collecting spatial, temporal and pressure data.	800	–
Gupta et al. [19]	An accelerometer and a pressure sensor to determine the orientation and type of grip, tuned for the replication of geometric shapes.	720	6
Saraswat et al. [38]	A system for monitoring writing, considering the location of the arm with respect to the orientation of the pencil.	620	5
Tapia et al. [39]	A smart writing tool that provides a presumptive diagnosis of an individual's anxiety levels.	745	7
Hnatiuc et al. [40]	Identification of emotions through a pencil that records the characteristic features of calm and agitated people.	560	5
Diaz et al. [41]	Data collection using a commercial digitiser tablet and stylus, to measure agonistic and antagonistic muscle neural responses.	950	–
Laniel et al. [42]	Analysis of the writing of children with attention deficit disorders (ADHD) using a commercial digitiser tablet.	950	–
Di Febbo et al. [43]	Identification of indicators of tremor in daily life, working with Bluetooth Low Energy technology.	690	6
Junior et al. [44]	Detection of dynamic writing parameters for the diagnosis of Parkinson's disease.	560	5

3. Experiment Context and Design

Our study took place in the San Juan de Jerusalén school of the city of Cuenca (Ecuador), an institution of inclusive basic education with 249 students, of which 61 have SEN—including cases of motor disability (infantile cerebral palsy), cognitive impairment, visual impairment and/or learning disabilities. The children with SEN follow the school's program according to their level, with adaptations of time and amount of material. They write slowly, large letters, in some cases illegible; however, they often compensate with greater auditory memory and verbal abilities, thus managing to carry out evaluations and tasks similar to those of their peers.

The study was based on criteria established jointly with a team of experts in the areas of speech therapy, occupational therapy, educational psychology, physiotherapy and pedagogy. As the writing instrument, we used the sensorised triangular prism pencil (henceforth, STPP) presented in [45], which provides measurements of force, position, speed and grip to a software system based on the algorithms of [19,44].

A total of 55 participants, from third and fourth grades, were picked randomly and organised into two evaluation groups (see Table 2):

- The control group, with 26 children (6 with SEN) who would only use the common pencil (cylindrical and thin).
- The intervention group, with 29 children (11 with SEN) who would use the STPP in the Language and Literature classes, and the common pencil in the rest of the subjects.

The only exception to the random assignment of children to the control and intervention groups was made with the ones who had special education needs, in order not to introduce bias related to their specific conditions. Thus, for example, two children affected by spasticity or motor stiffness would not be put into the same group unless there were others compensating the impact on the handwriting skills, according to the judgment of the experts from the school staff. That is the reason why there were 6 children with SEN in the control group, and a different number (11) in the intervention group.

Table 2. Composition of the intervention and control groups.

Grade	Group	Number of Students	Average Age	Students with SEN	Total Boys	Total Girls
Third	Intervention	16	7	5	10	6
Third	Control	14	7	2	7	7
Fourth	Intervention	13	8	6	5	8
Fourth	Control	12	8	4	4	8

By letting the children from the intervention group use both the STPP and the common one (and evaluating their skills with each one separately), we wanted to check whether the improvements attained by the use of the former were consolidated when the children used other writing instruments. The evaluations were made in such a way that the experts could neither recognise the children, nor tell whether the material corresponded to the pre-intervention or the post-intervention stage.

The flow of the experiment is shown in Figure 2. Firstly, children with and without SEN complete a test involving characterisation of forms, writing and free drawing. The results then entered a characterisation layer, where an initial evaluation was done by identifying most relevant graphomotor features. Following the teachers and therapists' supervision of those initial evaluations, the tests were quantified based on grip style, force exerted over the paper, calligraphy strokes and directionality. Four months later, a final evaluation took place in order to compare results.

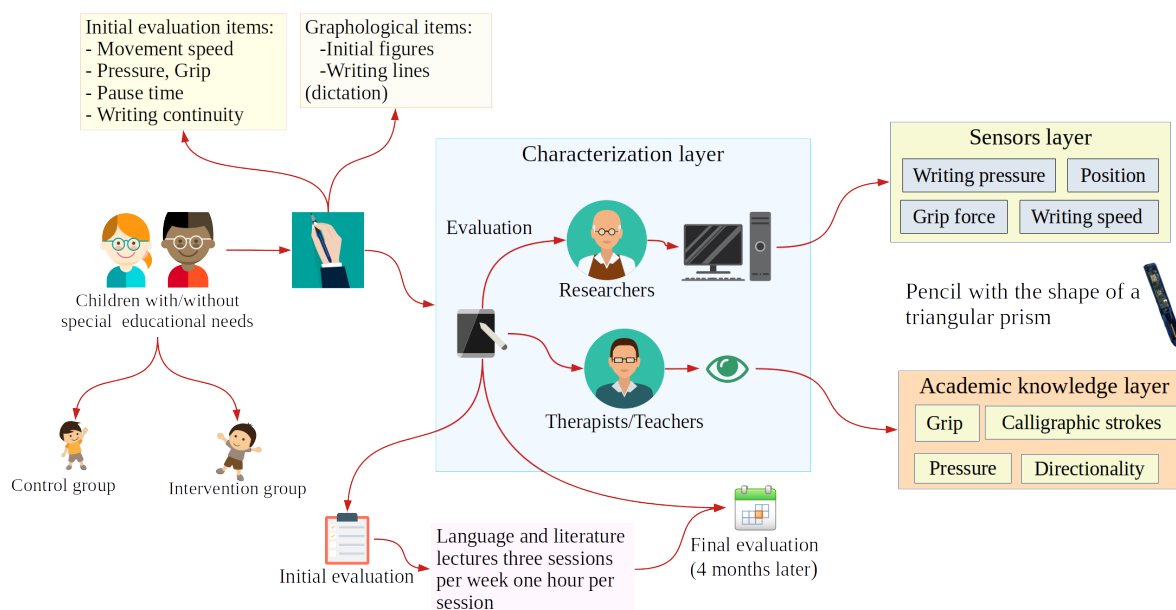


Figure 2. Experimentation proposal.

The assessment criteria looked at the four variables: grip, pressure, calligraphic strokes and directionality. Table 3 summarises the rubric:

- The preferred grip is tridigital and scored 3. The digital grip (i.e., the pencil is held at two points) scored 2, and the global grip (i.e., the pencil is held with the whole palm of the hand) scored 1.
- As regards the level of pressure exerted on the paper, low pressure scored 3, assuming that the child did not have hypotonia (low muscle tone), and strong pressure scored 1 when there was no hypertonia (excessive muscle tone).
- As regards the calligraphic strokes, continuous execution with constant speed scored as good (3). If there was hesitation (bursts of speeds in some lines with slight deterioration of the handwriting) the score was fair (2). If there were only bursts, straight lines where there should be curved ones, and/or unconnected strokes, the score was poor (1).
- As for directionality, when the stroke followed the established order, the score was 3. When that was not always the case, the score was 2. The score 1 was applied when the strokes were most often executed in ways that contravened the common patterns.

Table 3. The evaluation rubric.

Variable	Weight		
Grip	Tridigital (3)	Digital (2)	Global (1)
Pressure level	Low (3)	Moderate (2)	Strong (1)
Calligraphic strokes	Good (3)	Fair (2)	Poor (1)
Directionality	Good (3)	Fair (2)	Poor (1)

4. Results and Discussion

Next, we compare evaluations from the pre-intervention and post-intervention stages. The graphs of Figure 3 represent the percentages of children who got better scores after the intervention for each one of the experimental variables, applying the criteria of Table 3. The control group has one set of figures, because the children in it used common pencils only, whereas the intervention group has two sets: one corresponding to the skills observed when using the STPP, and another corresponding to the use of the common pencil.

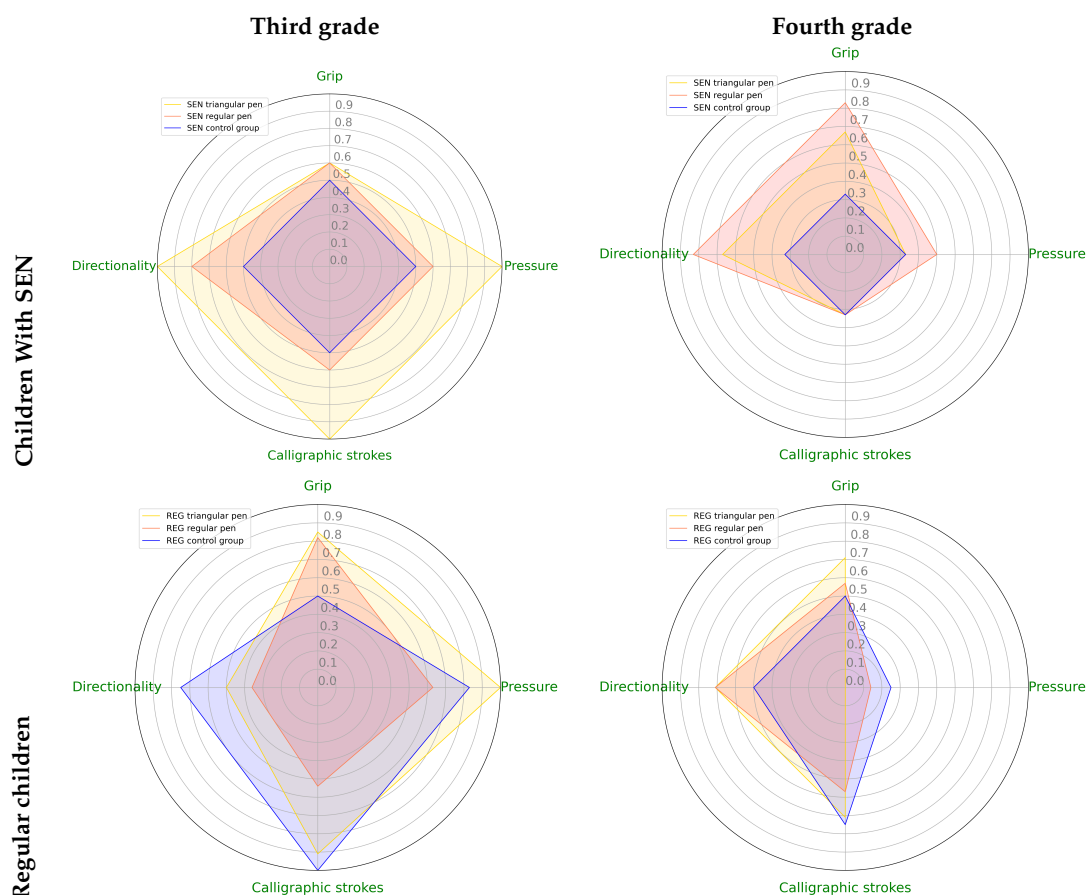


Figure 3. Summaries of the improvements observed in the control and intervention groups.

Among children with SEN from third grade, it can be seen that there was an improvement in all variables for 50% of those included in the control group. For the children in the intervention group, in turn, the percentage increased to 60% for grasp, pressure and calligraphic strokes, and to 80% for directionality when using the common pencil. With the STPP, better pressure, calligraphic strokes and directionality were noticeable in 100% of these children. These results show that the intervention made a difference among children with SEN at the early stage of acquiring handwriting skills. In the opinion of the therapists, the improvements observed in children with SEN are based on the fact that they struggle to attain fine motor skills. The STPP helps them grasp properly, because it offers them a visual and tactile reference so that their thumb, index and middle fingers can adapt to the shape of the pencil. Their condition requires greater effort to handle cylindrical and thin pencils.

In fourth grade, the percentage of children who improved their calligraphic strokes was 33% for both the control and the intervention groups, which we interpret as evidence that this skill is reasonably consolidated by the age of 8. As regards the other variables, the improvements in the usage of the common pencil were more frequent among the children in the intervention group: a 17% difference for pressure, 50% difference for grasp and 50% difference for directionality. The children in the intervention group improved their use of the STPP too, but to a lesser extent, suggesting that this instrument is easier for them to master than the common pencil, so at this age there is not so much room for improvement.

The results with regular children were significantly different. In third grade, the control group experienced greater improvements than the intervention group in terms of directionality (75% vs. 36%) and calligraphic strokes (100% vs. 54%), whereas the intervention group attained greater improvements in relation to the grip (82% vs. 50%). Besides, the children in the intervention group handled pressure better with the STPP (100% improvement), but their improvements with the common pencil were lower

in comparison with the control group (63% vs. 83%). The rate in which the improvements attained with the STPP persist when using other writing instruments deserves further investigation, as the experts from the staff of San Juan de Jerusalén school suggested that there must be one particular point in the learning process of each child that using different tools stops causing neuromotor confusion.

In fourth grade, the regular children in the intervention group improved their directionality more often than the control group (71% vs. 50%), and the use of the STPP proved advantageous in relation to the grip too. The children from the intervention group, however, experienced (11% vs. 18%) fewer improvements than those from the control group in terms of pressure and calligraphic strokes respectively. Indeed, out of 13 fourth-grade students in the intervention group, 2 complained about using the STPP as they felt muscular pain due to the pressure they exerted. The experts' explanation for these observations was that, by the age of 8, the children were already accustomed to using the common pencils, and providing them with a different reference required breaking a scheme that is mentally hard-wired already. In general, the older the kid, the more difficult it will be to mend wrong patterns learnt in the past.

It is interesting to note that, as evidenced by the area of the blue polygons of Figure 3, regular children from the control group (both from third grade and fourth grade) improved their skills more frequently than children with SEN of the same age. The experts from the San Juan de Jerusalén school said that this happened because the latter participate in extracurricular hours of speech and language therapy, occupational therapy and academic support offered by the staff. In consequence, notwithstanding their conditions, they are generally more advanced in trying to make the most of their capabilities than the regular ones.

As part of the validation of the STPP and the software we developed for the acquisition and analysis of quantitative data about handwriting, the experts provided the ratings shown in Table 4.

Table 4. Experts' answers to the technology acceptance questions.

Question	Very Positive	Positive	Neutral	Negative	Very Negative
Do you think it is useful to have a system for the acquisition and analysis of quantitative data about handwriting?	79.31%	17.24%	3.45%	0%	0%
Do you think the STPP is better than other possible choices to improve the pressure when writing?	82.78%	17.24%	0%	0%	0%
Do you think the STPP is better than other possible choices to improve grasp?	72.41%	17.24%	6.9%	3.45%	0%
Do you think the STPP is better than other possible choices to improve directionality?	51.72%	41.38%	6.9%	0%	0%
Do you think the STPP is better than other possible choices to improve calligraphic strokes?	62.07%	31.03%	6.9%	0%	0%
Would you like to take up the STPP in your classes, from the next academic year onwards?	82.76%	13.79%	3.45%	0%	0%

Systematically, more than 93% of their answers were very positive or positive, and none were negative or very negative. When asked about the STPP in relation to "other possible choices", the question explicitly included the type of add-ons enumerated in Section 2 as instruments to enforce particular types of grip. Overall, 79.31% of the staff thought the system (STPP + software) was very useful for their work, and 96.55% were willing to take up the technology in their classes from the next academic year onwards.

5. Moving on from the Positive Results: A Success Story from Cuenca, Ecuador

In the Ecuadorian province of Azuay, there are approximately 172 educational institutions with children studying in General Basic Education. Altogether, there are approximately 10,300 children between 4 and 6 who can improve their handwriting skills through the STPP. Following the positive results of Section 4, we were encouraged to assemble 50 pencils to cover the needs of 50 children from low-income families that receive therapy in the San Juan de Jerusalén school. For a month, 7 volunteers (5 interns and 2 research assistants) worked to fulfill the task. Ten professionals of the school supervised and provided support to validate the correct functioning of each pencil. The total amount required to make the 50 pencils was 2500 USD. We compared this cost with what we would have spent in mimicking the features of the devices presented by Junior et al. [44] and Di Febbo et al. [43], chosen according to the following criteria:

- Feasibility to build the pencil locally with low-cost 3D printers (this is determined by the complexity of the 3D model and the minimum size required to allocate the electronic components inside).
- Local availability of the electronic components to make the printed circuit boards.
- Novelty and functionalities: we wanted to compare with recent proposal able to yield the same data we needed in our experiment.

The total cost of assembling 50 units of the proposals by Junior et al. [44] and Di Febbo et al. [43] was 7560 USD and 9460 USD, which are roughly triple and quadruple of our STPP, respectively. Table 5 shows the investments needed to provide for the whole province:

Table 5. Estimated costs of manufacturing 10,300 sensorised pencils based on three different designs.

Equipment	Development Cost in Ecuador (USD)
Our proposal	$50 \times 10,300 = 515,000$
Junior et al. [44]	$(60 + 80) \times 10,300 + 560 = 1,442,000$
Di Febbo et al. [43]	$(90 + 80) \times 10,300 + 960 = 1,751,960$

Our proposal can be covered with 515,000 USD (50 USD per pencil) because we can use the network of volunteers and the support of numerous institutions—even if working with volunteers can extend the manufacturing times. To make the pencils according to the model described by Junior et al. [44], we would require 60 USD to buy the sensors, 80 USD for the workforce and 560 USD for software licenses. On the other hand, if we used the design presented in Di Febbo et al. [43], it would take 90 USD to buy the sensors, 80 USD for the workforce and 960 USD for software licenses.

With this background in mind, we decided to make 50 pencils to cover the needs of 50 children from low-income families that receive therapy in the San de Jerusalén school. For a month, 7 volunteers (5 interns and 2 research assistants) worked to complete the pencils. Ten professionals of the school supervised and provided support to validate the correct functioning of each pencil. The total amount required to make the 50 pencils was 2500 USD. The total amount to make the 50 pencils was 2500 USD, whereas the other alternatives would cost 7560 and 9460, respectively.

6. Conclusions and Future Work

Our experiment has shown that the sensorised triangular prism pencil, together with the software for the gathering and analysis of quantitative handwriting data, has a role to play in the acquisition of skills among third-grade and fourth-grade children. The results show that the geometry of the writing instruments does not have a significant influence, and that the benefits of using the ones that promote the best habits are most noticeable at early stages and, particularly, with children who have special education needs. Introducing the STPP in a stage that the handwriting skills are already mastered, or bad habits have already consolidated, is most probably neither advantageous, nor detrimental.

Having established the main guidelines to perform interventions in children with and without SEN, we plan to continue our work in the province of Azuay following a multi-layer sustainable development perspective based on collaboration of several institutions and individuals. The strategy is depicted in Figure 4.

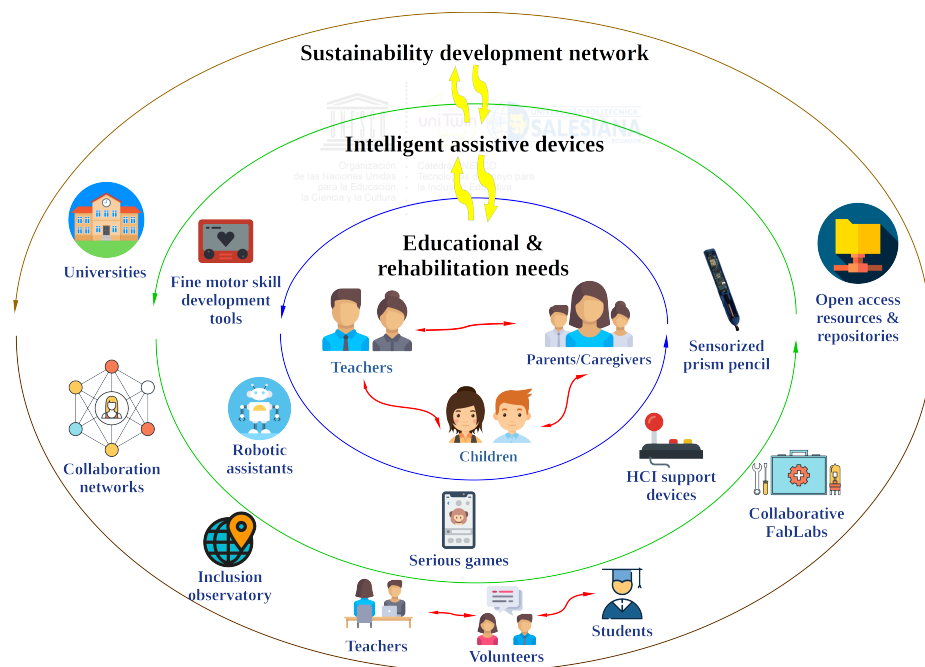


Figure 4. Schematic model to develop and deliver sensorised pencils to children from low-income families.

On a first layer, the main element are the children, their families/caregivers and their teachers. Each child is a different world with specific needs, skills, and desires. These characteristics are accentuated in cases of SEN or disabilities. For these reasons, is necessary to count on a set of tools that can be used according to each need and circumstance. These tools are provided in the second layer:

- Sensorised pencils that can be adapted to any size for children of different ages. Similarly, during the first stage, we can make only the case of the pencil and adjust its form to train the child.
- The human-computer interaction tools are fundamental to complement the interaction between children and technological devices such as computers, smartphones and tablets. These tools can be as simple as mouse or keyboard adaptations, or more complex such as brain signal readers.
- The serious games (currently under development) are very useful to motivate children being part of the therapy, and rehabilitation activities. Several studies have shown that children suffer less fatigue when they use serious games to carry out educational and rehabilitation activities [46].
- The introduction of robotic assistants in the different educational levels has changed the perspective of educational inclusion in the last years. With the support of proper robots it is possible to perform a wide range of activities for both education and rehabilitation.
- To complement the activities to develop fine motor skills with children, it is very important to continue using classical tools as puzzles, zippers, buttons, and in general, fine motor skill activities boards. These boards can be easily adapted to different children without losing their manual essence.

The third layer can be considered one of the most complex to put into practice due to the difficulty of achieving an appropriate articulation between all external participants and institutions. The most relevant elements of this layer are:

- The universities and research centers. These can be responsible for generating new designs of all tools used by professionals of regular and special education centers. Many universities in Ecuador

have FabLabs that can collaborate to develop educational tools. Likewise, the universities have students who, according to the Ecuadorian curricula, must complete community labor as part of their professional training process. These students can act as volunteers to fabricate the tools during their community service and pre-professional practices.

- The open-access resources and repositories. These can help to reduce significantly the time required to develop or adopt new technological solutions. Similarly, they can contain the results of different pilot experiments carried out during the validation of tools.
- The inclusion observatory. This is an essential element to collect data related to the development of new tools and support the creation of collaboration networks between research groups, education centers and volunteers.

Our early efforts in implementing this layered sustainability model have been largely successful, showing that is possible to generate awareness about volunteer activities in university students. Currently, we have created a network to support some requirements of children with/without SEN from low-income families. At the same time, the community can contribute by donating the electronic components that are available in the local market (instead of money). Similarly, a family with sufficient economic resources can afford the cost of materials and can help make two devices (one for themselves and one for a low-income family).

On the purely technological side, while the analysis of the handwriting data is currently left mostly for experts (through proper graphs and visualisations), we are working to define a set of descriptors that will allow capturing the most important characteristics of the strokes made by the children automatically, assign the corresponding achievement indicators: symmetry of the shapes, cuts, proportions, etc. The records from the experiment presented in this paper provide a first dataset for training a range of multi-modal AI systems. Additionally, in response to a request from the collaborating experts, we have initiated a study in a population of children of a younger chronological age, with the aim of detecting inappropriate writing habits from their first contact with a pencil at school.

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Abbreviations

The following abbreviations are used in this manuscript:

STPP	Sensorised Triangular Prism Pencil
SEN	Special education needs

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