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Quality Assessment of Braille Dots Printed by Fused Deposition Modeling 3D Printing Technology

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ABSTRACT

Braille is a universal tactile writing system for the blind and visually impaired. Braille can be printed in several ways, including embossing, screen, or UV ink-jet printing. In this study, we propose to use three-dimensional, 3D, printing technology to print dots of the Braille alphabet. The 3D model was designed with CAD software and then overprinted with Fused Deposition Modelling, FDM, technology with polylactide filament. Then, the quality of braille dots was assessed according to the standard for Braille. The estimated height (0.5 mm) and diameter (1.3 mm) for Braille dot were not achieved for the designed model. The measured values of the Braille dots were 0.38 ± 0.03 mm and 1.0 ± 0.07 mm for the height and diameter, respectively. The dot quality was assessed with an optical microscope. The distribution and location of the Braille can be acceptable, but the reproduction of dot shape, curvature, and dimensions is not compatible with the standard for Braille dots. Despite that, Braille is readable, and FDM can be a cheap solution to develop customized and unique plates with Braille imitating conventional Braille dots embossed in cardboard.

Keywords: 3D printing, blind, visually impaired, Braille, FDM.

INTRODUCTION

At least 2.2 billion people worldwide have a vision impairment or blindness [1]. The number of blind and visually impaired people is still increasing. Braille is a universal tactile writing system used by the blind in which a three-dimensional, 3D, dot-based script allows reading characters without the use of light or the sense of sight. Unlike classical writing, individual alphabet characters are convex and can be read by touching the fingertips. Louis Braille (1809–1852) invented the writing system that bears his name, the Braille or the Braille writing system [2]. This system could be "read" by touching with fingers [3]. In Braille, the sign comprises up to six dots arranged in two columns and three rows, corresponding to the appropriate letters or other characters [4]. By combining one or more dots in various positions, 64 combinations can be designed, creating letters, numbers, punctuation, mathematics characters, etc. [5]. According to the European Union directive, all pharmaceutical products must be labelled with Braille since 2005 [6]. Braille can be printed in several ways. The most common way is to emboss Braille dots on cardboard or paper of higher grammar. This method requires the preparation of an embossing matrix for each industrial product. Less often, other printing techniques are used for Braille labelling, i.e., screen printing and digital printing [7, 8]. Digital printing can be used for "short runs" because only a digital file must be prepared without preparing an embossing matrix or screen for a single pattern. UV ink-jet printing can print small elements such as Braille dots [9]. For short or single personalized runs, various 3D printing can be adapted.

Additive manufacturing, AM, has advanced rapidly in recent years [10]. AM can be divided into groups depending on the type of material used, the initial state of aggregation, the method of creating subsequent print layers, and the method of hardening the model. It is important to note that "3D printing" is more widely used for processes where polymers are building materials, while AM is more often for those with metals or ceramics [11]. However, AM methods aim to transfer 3D digital [i.e., CAD] models by layer-by-layer material deposition [12, 13], allowing the development of spatial objects. Initially, due to its inaccuracy, 3D printing was treated as a method of producing low-quality prototypes and molds for further production. According to the American Society for Testing and Materials (ASTM), there are seven categories of AM [12]. One of them is material extrusion, MEX, one of the most widely used additive technologies [13]. The most popular and available from MEX technologies is Fused Deposition Modelling, FDM. This process is characterized by extruding material from the nozzle layer by layer. The solid material as a filament is heated to melting temperature, extruded through the nozzle in the liquid state, and then cooled down. Among many various polymers for FDM 3D printing, most polylactide, PLA, is used due to its low cost, easiness of printing, and unique properties, such as higher density in comparison to the typical plastics [14, 15], low shrinkage [16], suitable thermal and rheological properties [17], biodegradability and biocompatibility [18].

With the development and improvement of 3D techniques, due to versatility, flexibility, and customizability, 3D printing has been found in many applications in various sectors of industry: aerospace, construction, food packaging, automobile, biomedical, etc. [19]. For example, 3D printing is successfully used for prostheses [20–22], tissues [21–26], patient-specific implants [27–29], music [30], sports [30], and even jewelry [31]. It is also worth mentioning that various AM technologies have been found to be applicable during the COVID-19 pandemic for fabrications of face shield and mask elements, valves, nasopharyngeal swabs, etc. [32].

3D printing can be successfully utilized for developing different 3D objects for the blind and visually impaired, for example, 3D tactile maps [8, 27, 33], cultural heritage objects by [34–37], tablets with Braille patterns [38,39], Braille-encoded intraoral films [40]. Furthermore, 3D printing can be applied in modern and innovative teaching of the blind and visually impaired, whereas 3D tactile objects improve teaching effectiveness [41–44]. Stangl et al. designed a 3D-printed tactile picture book based on a classic book for children with visual impairments [45]. Finally, relief models of artworks can be developed with various 3D techniques to improve the accessibility to art [46]. Additionally, 3D printing can successfully create prenatal models for blind and visually impaired expectant parents [47]. Last but not least, to print Braille for the blind and visually impaired, various 3D printing techniques can be applied, for instance, FDM, digital light processing, and PolyJet technologies [48]. Li et al. printed Braille plates using Chinese braille rules to develop puzzles for beginners to study Braille. Li et al. have noticed that the dot size error of elements printed by FDM is very large [48].

The work aims to apply FDM 3D printing technology for Braille printing for the blind to help with everyday functioning use. Nowadays, FDM 3D printers are easy to buy and cheap; the printer and filament prices start at around $200 and $25, respectively. FDM printers are low-cost and available compared to other AM methods and can be used in offices or homes. Hence, FDM printers can be easily adapted to prepare customized plates with signs for the blind and visually impaired. At the same time, paper and home office printers for printing Braille are much more expensive than an FDM filament and mid-range 3D printer. Furthermore, the price of customized information plates or labels with Braille signs starts at around 15$. The production of 3D-printed labels is less expensive.

It is crucial to prepare the blind and visually impaired in an environment where they can feel safe and access the required information. To our knowledge, no one has reported the quality analysis of Braille dots obtained using FDM printing technology compared to the Braille dots standard. The inscriptions must be readable for the blind and visually impaired and fulfill specific criteria. The study shows the process of creating a 3D model and assessing its quality. Firstly, a 3D model design using CAD software was created. Then, the design was exported to STL (standard triangle language) format. The model was 3D printed by FDM, and finally, the quality of the overprinted product and Braille dots was performed.

MATERIALS AND METHODS

The prints were performed with PLA (Polylactide, Filament PM, Chudobín, Czech Republic) and PET-G (Polyethylene Terephthalate Glycol, Spectrum, Pęcice, Poland) filaments. White PLA (Filament PM, Chudobín, Czech Republic) was used for final printing. The filaments were used as received. The filament properties are listed in Table 1.

The model was designed using Autodesk Fusion 360 (San Francisco, CA, United States). Before printing the final model suitable for further research, preliminary test prints were made to determine the selected parameters' correctness. The prints were printed with Ender 3 Pro (Creality-3D, Shenzhen, China) and Prusa i3 MK2S (Prusa Research, Prague, Czech Republic). The final printing was performed with Prusa i3 MK2S (Prusa Research, Prague, Czech Republic) according to the printing conditions in Table 2.

Samples of printed Braille dots were evaluated with Braille Dot Checker (BOBST, Mex, Switzerland). The measurements were performed according to the DIN EN 15823 standard [49]. For each dot, the dot diameter and dot height were measured. Additionally, the dot spacing was determined. The dots and the plate surface were observed with a digital microscope (Keyence VHX-7000, Japan) equipped with a VH-Z100R objective. The surface roughness, Ra and Rz, was analyzed at magnification 1000×.

SEM (JOEL JCM-7000) was applied to observe the surface structure of dots. The samples approx. 1 × 1 cm with a Latin and Braille later were fixed on the table with double-sided conductive adhesive. Then, they were covered with a thin layer of gold for SEM image determination. SEM images were received at an acceleration voltage of 15 kV.

DESIGN OF 3D PRINTING MODEL

The Braille alphabet has a form of small dots with specific dimensions. According to Article 54, the EU directive states that the name of a medicinal product must be expressed in Braille on the packaging [6]. The height and base diameter should meet specific technological standards so that texts labeled using Braille are legible to all blind people and do not show significant differences depending on the place of the production or manufacturer. The European and North American standards for pharmaceutical packaging and labeling recommend Marburg Medium font for pharmaceutical packaging and labeling [50]. In this work, we have used Poland Braille Fonts, which the Polish Association of the Blind recommends for small pharmaceutical packaging. The parameters of the Poland Braille Font allow for saving up to 10–12 percent less space on the packaging than the Marburg Medium font [51]. (Figure 1) The standard dot sizes and distances are listed in Table 3.

DISSCUSION

Printing the Braille alphabet did not cause major problems; however, a few attempts were made before the final model was overprinted. The overprinted Braille dots should meet proper standards, such as height, diameter, and the distance between dots. The final print is shown in Figure 2a). The initial quality assessment allows us to

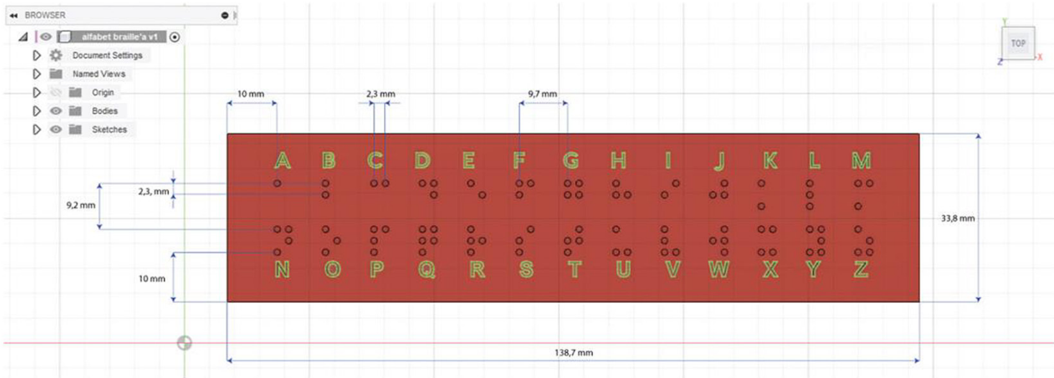
Table 2. Printing conditions on Prusa i3 MK2S

Property	Value
Nozzle temperature (°C)	215
Table temperature, providing constant printing conditions (°C)	60
Nozzle diameter (mm)	0.4
Filament diameter (mm)	1.75
Layer thickness (mm)	0.1
Printing speed	40 mm/s
Fill (%)	15
Time (min)	84 min

Table 1. Properties of printing material

Property	Value	
Composition	Polylactide	Polyethylene terephthalate glycol
Abbreviation	PLA	PET-G
Filament thickness (mm)	1.75	1.75
Color	white, green	black
Softening temperature (°C)	55	70
Density ($g \cdot cm^{-3}$)	1.24	1.18

a)



b)

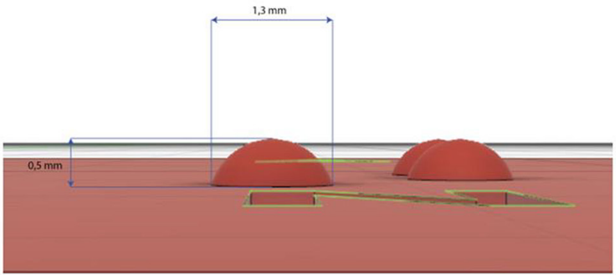
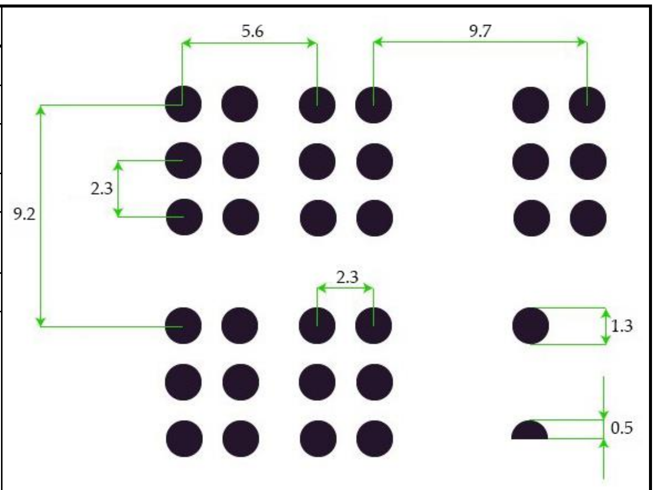


Figure 1. The final CAD plate model with the Braille alphabet is (a) the entire plate and (b) a letter model

Table 3. Position of Braille dots within a cell, spacing dimensions, dots diameter, and height in mm according to Poland Braille Font

Position of dots in mm	
Dot height	0.5
Dot down diameter	1.3
Dot spacing from dot center to dot center horizontally or vertically	2.3
Character spacing from dot center to dot center	5.6
Cell spacing from dot center to dot center with single spacing	9.7
Line spacing	9.2
Dot height and diameter reproduction tolerance	± 0.1



assume that the print is correct. The edges of the tile and the outlines of the Latin letters are sharp and clear. Individual Braille dots were reproduced correctly, without unintentional contaminations and errors. Braille dots and characters can be felt with fingertips, and their reception is not disturbed by unwanted protrusions, as with test prints. The ground surface between the points is smooth.

The final printing parameters were adapted based on trail prints' results (Figure 2b) and visual evaluation. To correctly assess the quality of the obtained plate, the size of the entire model was measured with a caliper and hand-held micrometer, i.e., the plate's width, height, and thickness. The received dimensions were 138.68 mm, 33.71, and 2.96 mm for width, height, and thickness,

a) b)

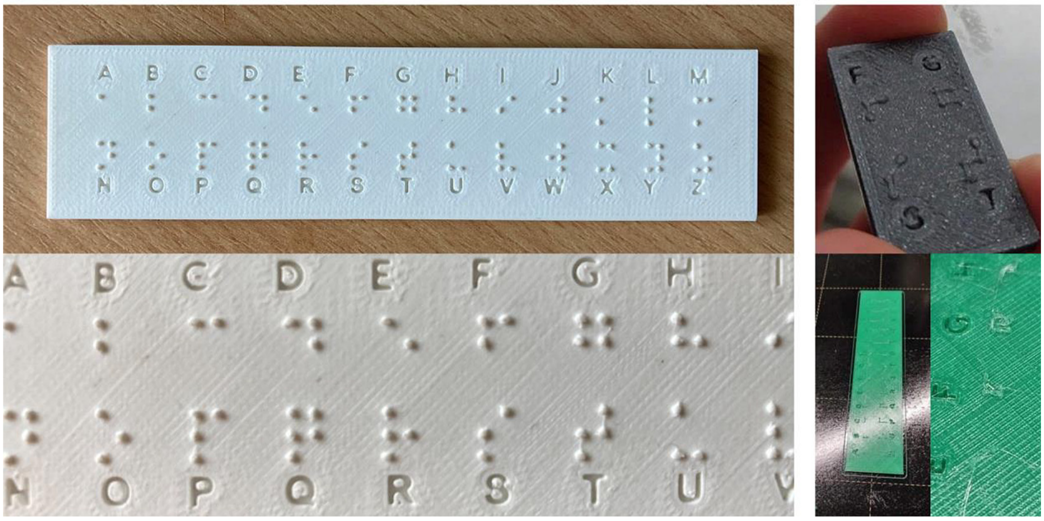


Figure 2. The printed model of Braille alphabet (a) final model; (b) unsuccessful trial printing of designed model

respectively, and differ slightly from those planned in the CAD model. This effect might be related to the slight shrinkage of PLA [52].

Finally, the correctness of the dimensions of the dots obtained on the print was tested. Figure 3 shows the images of Braille dots taken with the Braille Dot Checker. This device allows non-contact measurement and analyses of the printed dots' mapping, shape, and deformation.

A visual analysis of Braille dots shows the inaccuracy of reproducing the shape of the designed dots. The overprinted Braille dots are flattened at the top and have sharp edges, resembling a truncated cone (see Figure 3a). Under magnification, the horizontal lines mark the connection dots of additional layers of the PLA material. It is an effect resulting from the characteristics of the additive 3D printing technique. It can be noticed that the layers of the print (i.e., the tops of the dots) were not perfectly matched to the ones below, which resulted in the next layer of material shifting relative to the base and disturbing the rounded shape of the dots. For individual dots, it is possible to observe dirt and undesirable protruding fragments of material known as string, as shown in Figure 3, caused by material leaking or dragging from the nozzle when moving the print bed between printing subsequent points located at a distance. The captured

a) b) c) d)

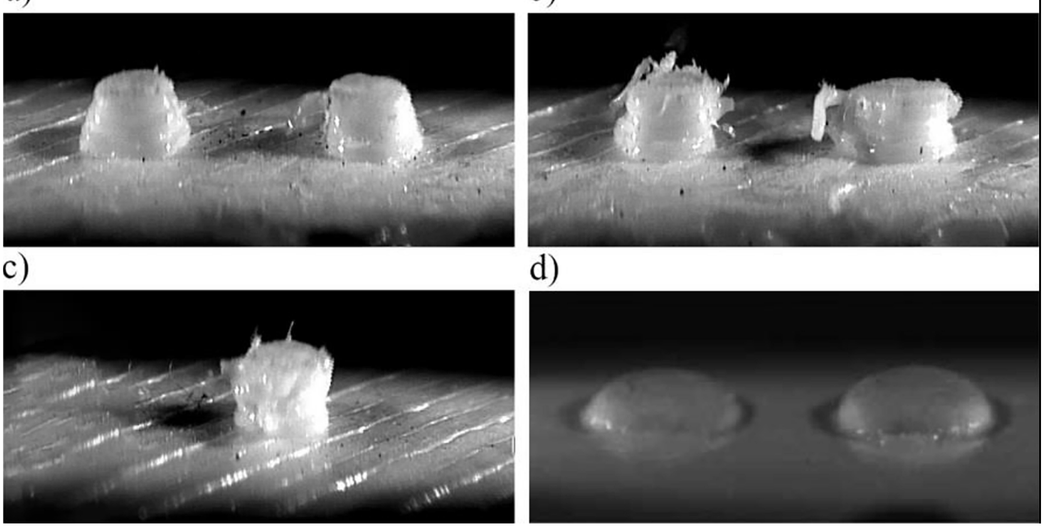


Figure 3. Reproduction of Braille dots (a) correctly, (b) with some contamination and (c) with some deformation, (d) embossed dot in cardboard

photos also show diagonal lines on the surface of the substrate between the dots, which indicates the rough surface of the tile and low smoothness. Some dots did not achieve the round shape typical of Braille dots, as shown in Figure 3c. The properly embossed Braille dot is shown in Figure 3d.

The measurements of dot height, diameter, and spacing between dot centers are summarized in Table 4. The overprinted model did not achieve the estimated height and diameter for dots. The measured height values of the dots are in the range of 0.31–0.43 mm, with an average value of 0.38 ± 0.03 mm. The diameter measurements range from 0.86 to 1.14 mm with an average value of 1.0 ± 0.07. The overprinted dots do not reach the expected diameter value of 1.3 mm. The obtained spacing of the dots is in the range of 2.13–2.28 mm with an average of 2.22 ± 0.05 mm and, like other dimensions, is smaller than the estimated value of 2.3 mm. All the dimensions, except the spacing between the dots, have less tolerance, which is acceptable for Braille dots, according to Poland Braille Font [51].

The surface roughness was assessed by R_a and R_z roughness parameters, where R_a indicates the average roughness of a surface and R_z is the difference between the tallest "peak" and the deepest "valley" of the surface. The R_a and R_z values were 1.30 and 6.86 µm, respectively. Figure 4 shows the surface profiles of samples determined by a digital microscope. The unevenness of the surface of the printed plate is visible by the naked eye, which is related to the printing process, in which layer by layer is applied during the transition line of the nozzle with the filament (see Figure 4a).

The microscope observation of dots reveals that Braille dots are developed with up to four layers of material. For example, a dot in the letter "j" consists of 4 layers (see Figure 5a), and a dot in the letter "z" consists of only two layers (Figure 5b). The microscopic observation confirmed the stringing of additional PLA material (Figure 5c). To confirm this observation, SEM micrographs were taken (Figure 6). Figure 6b shows the characteristic four layers of PLA in Braille dots with

Table 4. Measured values of dot height, diameter, and spacing between dot centers

Property	Estimated value in mm	Value in mm	Minimum value in mm
Dot height	0.5	0.38 ± 0.03	0.31
Diameter	1.3	1.00 ± 0.07	0.86
Dot spacing from dot center to dot center	2.3	2.22 ± 0.05	2.13

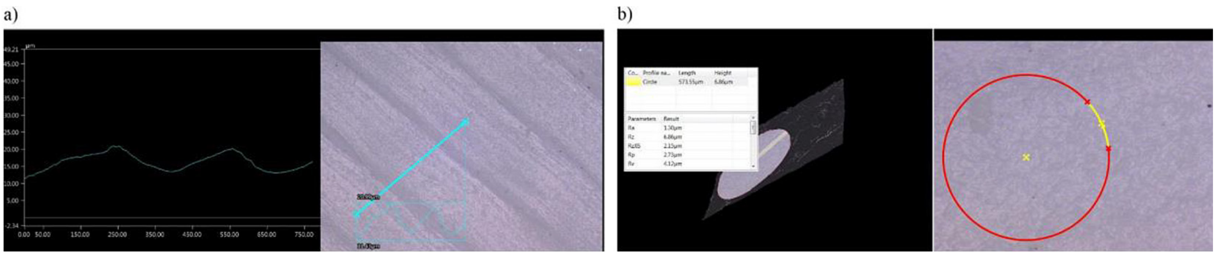


Figure 4. Image of the developed base surface using digital microscope at magnification (a) 200×; (b) 1000×

Figure 5. The microscopic images of Braille dots taken and magnification 100× (a) dot in letter "j", (b) dot in letter "z" (c) stringing between dots

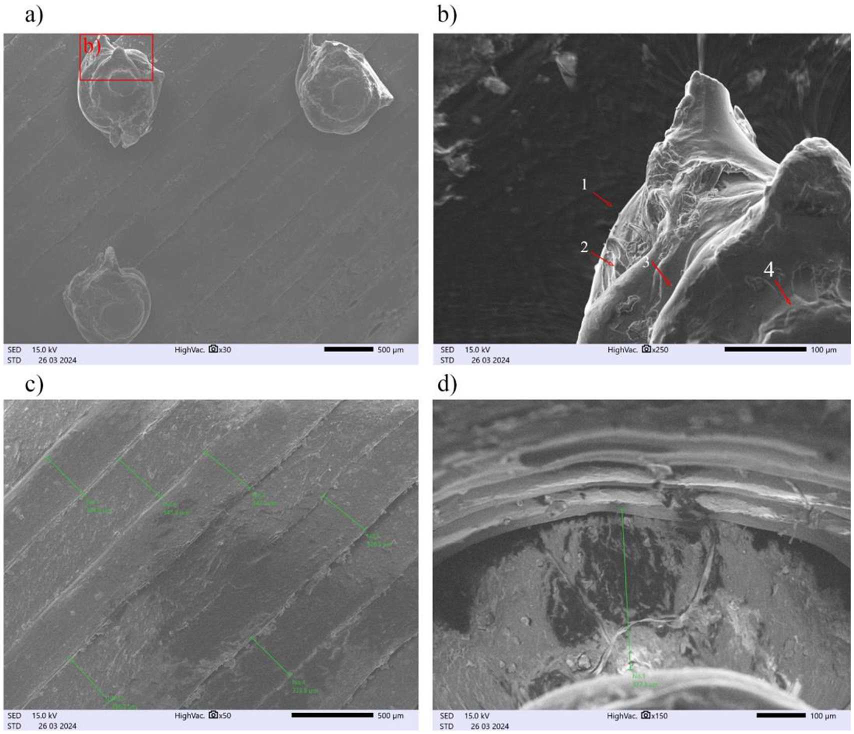


Figure 6. SEM micrographs of dots: (a) dots in letter "q," (b) dot with four layers, (c) plate surface with a characteristic line, (d) fragment of Latin letter "o"

some contaminants and stringing of material. Urbas et al. have also confirmed the presence of four layers [8]. The plate has characteristics of "lines," which are related to the transition line of the nozzle with the filament. The line has a width of 340 ± 11 μm and might be felt with a fingertip. The posttreatment (polishing) of dots and plates can make the edges of the dots smoother and more pleasant to feel, but this requires an additional operation, increases the cost of the label, and may not be available to do at home.

CONCLUSIONS

This study aimed to print Braille dots using Fused Deposition Modeling 3D printing to assess whether FDM technology allows obtaining standardized and legible prints for blind people. The main aspect of using 3D printing for Braille is its universality, availability, and low price, allowing the production of low-volume prints with short runs or single prints on demand without needing extensive technical resources or external companies' services. The construction of spatial Braille dots illustrating the alphabet placed according to specifications for Poland Braille Fonts standard was prepared. The model was intended to imitate conventional Braille dots, which can be embossed on cardboard. The appropriate parameters of FDM 3D printing were adjusted to achieve the best possible results on the 3D printer for the office or home environment. Among the available materials, PLA was used due to its ecological nature, low price, and good printability.

The results show that achieving the estimated dimensions of the Braille dot was impossible. Unfortunately, the Braille dots were not reproduced satisfactorily. Reproducing the curvature shape of the dots turned out to be problematic. Ultimately, the dots should be rounded and their edges completely smooth. The points obtained in the print resemble truncated cones with sharp edges around the upper, flat surface. This effect is related to the characteristics of the FDM additive technology. Obtained shape can negatively affect their readability. The enlarged image captured during the examination shows horizontal lines indicating where combining layers are joined. To avoid these errors, it might be necessary to use additional post-processing, e.g., smoothing. However, post-processing can negatively affect the dimensions of individual dots. Additionally, undesirable "spots" of hardened filament appeared on the printout, creating noticeable surface irregularities under the fingertip. The entire surface of the board is rough to the touch, so additional smoothing would also be required in the post-production process to ensure that the reception of the content expressed in Braille inscriptions was undisturbed.

Summarizing the results of the overprinted model with FDM 3D printing technology, the distribution, and location of the Braille can be acceptable. Still, the reproduction of their shape, curvature, and dimensions was lower than the dimension tolerance for Braille dots. However, despite geometrical defects, FDM can be a cheap solution for the blind to develop plates with Braille signs on-demand or, in the short run, unique and customized, which helps them in life functioning.

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