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Was a 3D-printed firearm discharged? Study of traces produced by the use of six fully 3D-printed firearms

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ABSTRACT

Since the blueprints of the Liberator were published and successfully tested, countless new designs for said 3D-printed firearms and 3D-printed firearm components have been created and made publicly available. These new 3D-printed firearms, which are praised by their designers as ever more reliable, can be found on the Internet with little effort. Press reports have shown that various models of 3D-printed firearms have already been confiscated by law enforcement services around the world. So far, forensic studies have addressed this set of problems relatively little, whereby for the most part only the Liberator has been examined in detail and three other designs were only included a few times. The rapid pace of this development poses new challenges for forensic investigations and unveils new spheres of investigation regarding 3D-printed firearms. This research initiative aims to determine whether the results from previous studies on Liberators, are also reproducible and observable when using other models of 3D-printed firearms. In this respect six fully 3D-printed firearms – PM422 Songbird, PM522 Washbear, TREVOR, TESSA, Marvel Revolver and Grizzly – were produced on a material extrusion type Prusa i3 MK3S using PLA as the material. Test firings of these 3D-printed firearms have shown that they are indeed functional, but that, depending on the model, they suffer different levels of damage when fired. However, they were all rendered inoperative after one discharge and could not be used for further discharges unless the broken pieces were replaced. As in other studies, the firing process and the resulting ruptures on the 3D-printed firearm, projected polymer parts and fragments of different sizes and in different quantities into the immediate environment. The parts could be physically matched, allowing the reconstruction and identification of the 3D-printed firearms. Elements of ammunition also showed traces of melted polymer on the surface and cartridge cases bore tears or swellings.

1. Introduction

Since the release of the blueprints of one of the first 3D-printed firearms, named the Liberator by Cody Wilson and the organization Defense Distributed, several communities arose with the intention to pursue the development of new designs for 3D-printed firearms. The corresponding blueprints and other relevant files can be found and downloaded in minutes on the clear web. The availability of the files, as well as the ever-increasing accessibility of 3D-printing equipment, facilitates the fabrication of such firearms so that even ordinary people without any prior knowledge would be able to produce homemade firearms. Thus arises the problem of circumventing laws on firearms production and possession. Moreover, the mentioned firearms are labelled as “ghost-guns” which do not have a serial number and therefore are untraceable [1].

Regarding the classification of 3D-printed firearms, the ARES (Armament Research Services) Desktop Firearms report established three categories for said firearms: (i) Fully 3D-printed (F3DP) firearms, (ii) Hybrid 3D-printed firearms and (iii) Parts Kit Completions/Conversions (PKC) [2]. F3DP firearms are composed mainly of parts produced by 3D printing, generally in polymer, especially the essential parts of the firearm such as the barrel, the frame and the breech. The use of other components is restricted to certain small parts, for example, nails serving as firing pins or rubber bands used as springs for movable parts. Hybrid 3D-printed firearms, on the other hand, integrate non-regulated or non-restricted parts (e.g., springs, screws, nails, metal tubing) in their designs to enhance

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mechanical properties of the firearm. These hybrid firearms are deemed to be more reliable and sophisticated than F3DP firearm designs. The last category, PKC, is comprised of 3D-printed firearms which use 3D-printed parts for the assembly, but most parts are commercially available and come from conventional firearms. Examples of this category are 3D-printed frames for Glocks or lower receivers for an AR-15. The three categories differ in various respects. While F3DP firearms are easy to manufacture, they have poorer mechanical properties (e.g., resistance, toughness) than the two other categories.

Several cases in which 3D-printed firearms were seized by the police were already reported by the media. During the investigation of the Halle synagogue shooting in 2019 in Halle, Germany, Police seized a 3D printer with which the perpetrator apparently fabricated parts for the Luty 3D-printed firearm [3]. More recently, the Spanish police released a statement indicating that they had dismantled a workshop in which 3D printers were used to fabricate firearms and parts for conventional firearms [4]. These selected examples show that many different 3D-printed firearms or 3D-printed firearm parts are printed making use of the large choice of designs made available by several communities.

The points stated above outline the new challenges the 3D-printed firearms pose not only for security policy but also for the work of the law enforcement services. It also includes forensic issues and requires investigation and examination strategies to be adapted to address the full potential of information and traces created during the production and utilization of these 3D-printed firearms. To date, only a few studies have been undertaken to provide data and knowledge on 3D-printed firearms in a forensic perspective. Some published projects focused on the chemical analysis of the polymer used in the fabrication [5–7], whereas detailed studies about the traceology of the discharge of such firearms are scarce [8]. Projects about the Liberator studied, in more detail, the traces generated by the discharge, and they developed a piece of core knowledge about this 3D-printed firearm [7–11]. This is not the case for the other 3D-printed firearms models, which have been much less studied. More scientific research is needed to fill this gap of knowledge in the domain of 3D-printed firearms. Hence, the aim of this project is to conduct first experiments with various models of F3DP firearms to (i) examine the functionality and reliability of the chosen F3DP firearms and (ii) study the traces generated after the discharge. This encompasses the traces left on the elements of ammunition as well as the polymer fragments which may be found in the surroundings of the discharged firearm. Together with findings from previous studies, these experiments contribute to understanding the trace production resulting from the use of F3DP firearms, as well as the investigative possibilities associated with such firearms. Thus, the tests that have been carried out in this research aimed to exemplify the behavior of F3DP firearms but did not intend to offer an exhaustive study of the traces produced by F3DP firearms.

2. Method

2.1. Selection criteria

Blueprints in the format of STL files (Stereolithography or Standard Triangle/Tessellation Language) were collected only on the freely accessible clear web. Other types of files (e.g., ReadMe.txt, renders and instructions) were often present in the same folder as the STL files and were downloaded as well. The selection of the firearms for the present study is based upon the following criteria:

– The firearm is almost fully 3D-printed (F3DP);
– It is proven or deemed to be functional;
– The blueprints and assembly process are available freely on the internet;
– The allowed, non-printed pieces are the firing pin, rubber bands, and a few nails and screws at most.

This resulted in a selection of six F3DP known under their designations as PM422 Songbird, PM522 Washbear, Project TESSA (Tactically Enhanced Songbird Similar Armament), TREVOR (Tiny Revolving Effective Vehicle Of Resistance), Grizzly Handgun and Marvel revolver. They are referred to as Songbird, Washbear, TESSA, TREVOR, Grizzly and Marvel in the rest of the report. This selection is comprised of three revolvers (Washbear, TREVOR, Marvel) and three single-shot 3D-printed firearms (Songbird, TESSA, Grizzly).

2.2. Printing

First, all available files were searched for information and instructions for the printing. Then, the printing process started by creating the command file for the 3D printer, known as G-Code, using a Slicer software. PrusaSlicer Version 2.3.0 was used to prepare the objects for the prints. The standard printing profile “0.20 mm Quality” with a layer height of 0.20 mm and two perimeters was selected. Infill density was set to 100% and support material was added depending on the object’s geometry. The remaining printing parameters were left as defined in the printing profile.

In the case that some parts needed digital modifications to permit the assembly or the functionality, the according STL files were modified in Autodesk’s Fusion 360 (California, USA) modeling software. This was the case for the TESSA, TREVOR and Grizzly.[1]

The printer used for this project is an Original Prusa i3 MK3S (Prusa Research a.s., Prague, Czech Republic). This printer is based on the printing process ‘Material Extrusion (ME)’ as defined by the ISO & ASTM F42 Committee [12]. One specimen per firearm was printed, using polylactic acid (PLA) NX2 filament of 1.75 mm diameter manufactured by Extrudr (Bregenz, Austria). Printing temperatures were set at 210 °C for the nozzle and 55 °C for the printing surface. These temperatures were defined through successful calibrations of the printers and according to the manufacturer’s instructions.

The printed pieces were removed from their support and sanded in order to smooth any unwanted protrusion. Some pieces were slightly adjusted if it was deemed necessary, in order to assemble the whole firearm.

2.3. Assembling process

The firearms were then assembled following guidelines that may be provided along with the blueprints on the Internet. Non-printed parts, such as firing pins, rubber bands or screws, were fabricated or bought, depending on the model. Nails serving as the firing pin are not interchangeable between the firearms and need specific dimensions. Therefore, nails were bought from a local hardware shop and modified accordingly. Except for the Grizzly, different types of rubber bands were used to enable the striking of the hammer and the firing pin, or for the movement of some other movable parts such as a trigger. For the Songbird, TREVOR, TESSA and Marvel, rubber bands of medium and large size were purchased from another local hardware shop. For the TREVOR and Washbear, strong pull (1.8 N) intraoral latex elastics of 6.4 mm diameter were acquired from Dentaurum (Ispringen, Germany). The Marvel and the TREVOR were the only firearms which needed screws to hold together different parts of the model. The six F3DP firearms before assembly are illustrated in Appendix, Figs. A1 to A6, and as assembled in Fig. 1. The number of printed and non-printed parts (such as rubber bands,

[1] Detailed information on the modifications and on assembly that allowed the firearms to be functional is not presented publicly in this article. The authors can be contacted for this detailed information.

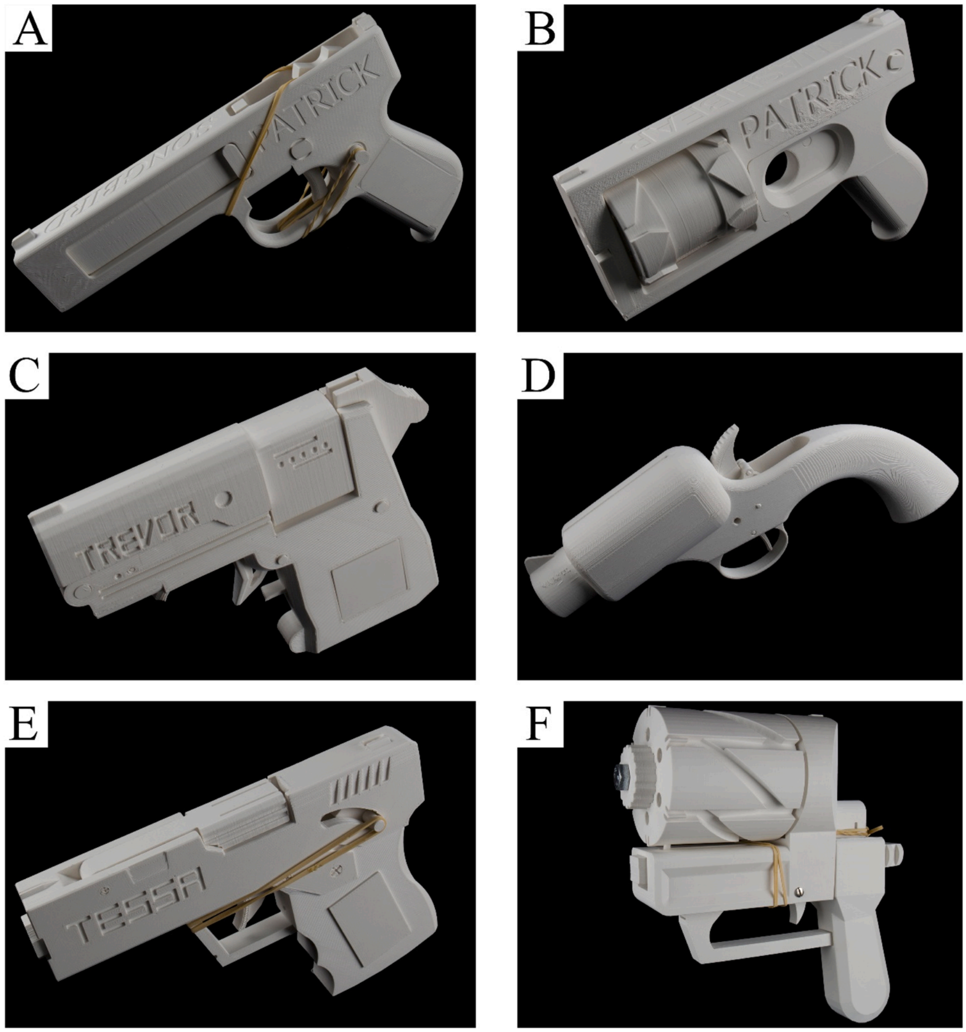

Fig. 1. All fired 3D-printed firearms: (A) PM422 Songbird, (B) PM522 Washbear, (C) TREVOR, (D) Grizzly, (E) TESSA, (F) Marvel.

Table 1
Specifications of the tested 3D-printed firearms.

Parts	Songbird	Washbear	TREVOR	Grizzly	TESSA	Marvel
Printed parts	8	13	9	12	8	10
Non-printed parts	3	10	5	1	2	10
Barrel length	109 mm	72 mm	110 mm	107 mm	115 mm	94 mm
Ammunition capacity	1	6	2	1	1	6

springs, screws, and the nail acting as firing pin which was used in all F3DP firearms) and other technical specifications of the firearms are stated in Table 1. The information on the length of the pistol barrel also includes the length of the chamber.

2.4. Test-firing process

The ammunition used for the experimentations is adapted to the firearm in question and specified in Table 2. For firearms using .22 Long Rifle, ammunition from the same batch was used for all the discharges.

All discharges were conducted in an indoor shooting range as described in Fig. 2. The floor and the walls were covered with clean paper up to a height of approximately 1.80 m. Before and after each discharge, pictures of the firearm and of the general setup were taken (Canon EOS 6D) and each discharge was also filmed in slow motion on a Samsung Galaxy S10 (Full HD 1080p, 30 fps). Between each discharge, the paper on the floor was swept and vacuumed. The shooting target was ballistic soap (glycerine soap, 25 × 25 × 40 cm) from Mettler-Seifen AG, Switzerland. A Drello Bal 4050 Counter (Drello GmbH, Germany) velocity measuring system was used to determine the projectile's velocity. The firearms were mounted on a firearm Ransom rest (Ransom International Corporation, USA) which was set up 3 m away from the target. For safety reasons, a protection glass was placed behind the 3D-printed firearm, and it was discharged using string attached to the trigger.

2.5. Traces collection and analysis

After a successful discharge, all pieces from the 3D-printed firearm were first collected by hand and conditioned in Minigrip® plastic bags, while fragments were collected by tapping the floor with adhesive sheets. The 3D-printed firearm and ammunition elements were also collected and conditioned in separate Minigrip® plastic bags. In case the bullet reached the target, the ballistic soap

Table 2
Ammunition used in the test-firing procedure depending on the firearm.

Caliber	Firearm	Ammunition
.22 Long Rifle	Songbird, Washbear, TREVOR, Grizzly	Remington, High Velocity, 40 gr/2.59 g, Solid point Nominal velocity: 380 m/s
9 × 19 mm Parabellum	TESSA	Geco, 124 gr/8.0 g, Full Metal Jacket (FMJ) Nominal velocity: 360 m/s
.38 Special	Marvel	Magtech, 38Q, 125 gr/8.10 g, FMJ-FLAT Nominal velocity: 285 m/s

was examined in order to observe the trajectory and depth of penetration.

The firearms, elements of ammunition and traces were documented using a Canon EOS 6D and observed with a Leica M125 stereomicroscope (Leica Microsystems GmbH, Germany) under different magnifications. In addition, a Polilight PL500 (Rofin Australia Pty Ltd, Australia) was used to observe potential polymer depositions under different wavelengths of illumination.

3. Results and discussion

3.1. Test-firing process

The following results concern solely the 3D-printed firearms printed in PLA for this project. The results may differ when using different materials such as ABS (Acrylonitrile Butadiene Styrene) or nylon filaments. Moreover, some STL files for specific pieces had to be modified and manufactured in order to allow the successful firing of the associated 3D-printed firearm. The six F3DP firearms managed to fire one shot after several tries, and none of them survived completely or without broken parts at the discharge. They were all considered unusable, as they had either exploded or part of the 3D-printed firearm was broken. Thus, each firearm was only used once, even though parts could have been swapped out to render the firearm functional again.

We will first discuss the impact of the discharge on the 3D-printed firearms and the traces it may have left in the environment, then consider the elements of ammunition and lastly the resulting traces on the 3D-printed firearm. Table 3 gives an overview of the results obtained for the six discharges.

3.1.1. Impact of the discharge

Among the six discharges, the barrel was found attached to the intact frames with three firearms: Songbird, Grizzly and Washbear; it was ejected with part of the frame with the Marvel. The TREVOR and the TESSA exploded during the discharge, resulting in fragments being ejected in all directions. With these two 3D-printed firearms, the cartridge case was also ejected into the surrounding area as the chamber could not withstand the pressure generated during the discharge. The cartridge cases were found inside the barrels for the four others. When functioning correctly, the cases should remain in the barrel or cylinder and be removed manually by the operator for the six F3DP firearms tested. The state of the F3DP firearms after the discharge is displayed in Fig. 3 and A7–A12 in Appendix.

More specifically, no piece was ejected away from the Grizzly, but some fragments were collected on the scene, and the 3D-printed firearm appeared to remain intact (Fig. 3D and A10). In the cases of the Songbird and the Washbear, only one piece for each was retrieved away, respectively on the left side of the barrel, at the 3D-printed firearm's height (stuck in the wall) and on the right side of the barrel, on the ground (Fig. 4A). No other pieces or fragments were recovered in front or behind these two F3DP firearms.

After the discharge of all of the 3D-printed firearms, a few small polymer fragments and mainly gunshot residues (GSR) of unburnt and partially burnt particles, were collected on adhesive sheets. It was explained in previous research that even those small polymer fragments could allow one to determine or measure different printing features set during the printing process [8]. Some much smaller fragments, dust like particles, were also collected with the adhesive sheets. With further analytical methods, the nature (polymer) of those particles could be determined. This would help to differentiate them or not from possible background noise. In this context, it is assumed that those particles originated from the interior of the barrel and were scraped by the passing of the projectile. The presence of polymer fragments or particles on the investigation scene proves to be an important trace to point to the use (discharge) of a 3D-printed firearm. These traces make it possible to differentiate the use of a metal homemade or improvised firearm such as a pipe gun, a zip gun or a converted firearm, from a 3D-printed firearm.

The cylinder of Marvel was broken in two parts, and the rod used to attach the cylinder onto the frame was ejected along the cylinder, in front of the 3D-printed firearm after firing (Fig. 4B). The quantity of polymer fragments collected on the adhesive sheet was also superior to the Grizzly, the Washbear and the Songbird. A lot of elongated fragments, made of one layer of polymer, along with many rectangular and square fragments, were collected.

The frame of the TESSA exploded for the most part, and only the grip and the back of the frame were still attached to the ransom rest. Big and middle-sized fragments were recovered from all around the 3D-printed firearm, as far as the end of the firing range. The nail used as a firing pin and the cartridge were also recovered in front of the 3D-printed firearm, on the left side (Fig. 4C). The largest quantity of

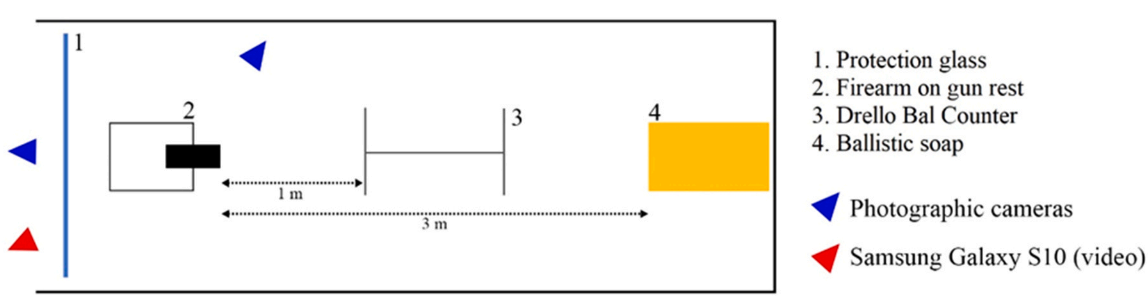

Fig. 2. Schematic plan view of the firing-test full setup, the photographic cameras are removed from the shooting range during the discharge.

Table 3
Velocity, state of the barrel after the discharge and depth of penetration in the ballistics soap. MU indicates the measurement uncertainty for each measurement.

F3DP firearm	Caliber	Velocity [m/s], MU = ± 1 m/s	Condition of the discharged F3DP firearm	Bullet penetration in the ballistic soap [cm], MU = ± 0.1 cm
Songbird	.22 Long Rifle	91	Broken barrel	5.0
Washbear	.22 Long Rifle	–	Broken cylinder	-
TREVOR	.22 Long Rifle	71	Exploded	3.7
Grizzly	.22 Long Rifle	93	Broken barrel	7.3
TESSA	9 × 19 mm Parabellum	45	Exploded	2.7
Marvel	.38 Special	109	Broken	12.4

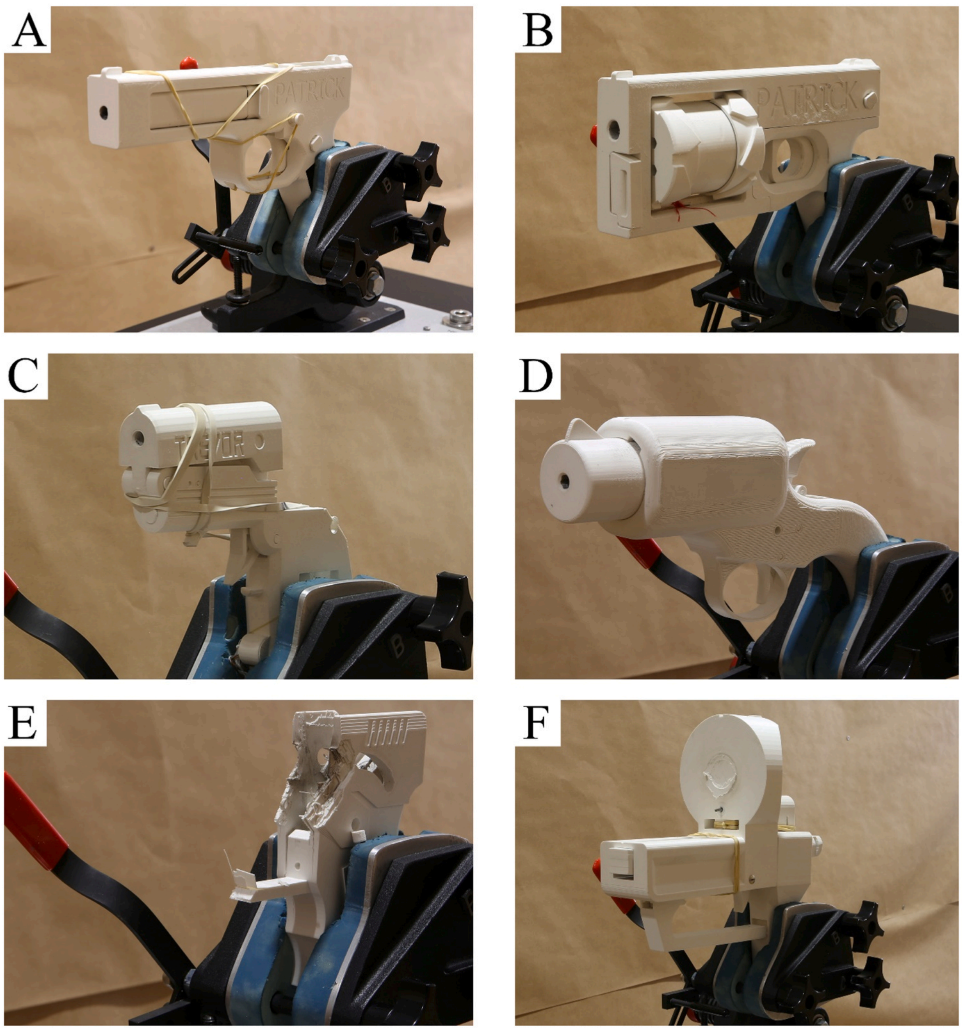

Fig. 3. All fired 3D-printed firearms after the discharge: (A) PM422 Songbird, (B) PM522 Washbear, (C) TREVOR, (D) Grizzly, (E) TESSA, (F) Marvel.

polymer fragments was also collected on the adhesive sheet along with unburnt particles. A large number of small fragments, as stated in the case of the Marvel, but also a significant amount of debris from the ceiling of the shooting range (as it was not covered with paper), indicates that a large number of pieces and fragments from the 3D-printed firearm were thrown towards the ceiling and altered the coating.

The back of the frame broke, and the cylinder of the TREVOR, along with the hammer and other pieces, were expelled away from the 3D-printed firearm, while the bottom half of the frame (grip and barrel) remained intact. No parts were projected in front of the 3D-printed firearm and all fragments were collected behind it, as far as a few meters away (Fig. 4D). A smaller amount of polymer fragments was collected with the adhesive sheet than with TESSA and Marvel. Moreover, many partially burnt and unburnt particles were recovered as well.

3.1.2. Traces recovered in the environment

As noted above, polymer fragments of various sizes, GSR and unburnt particles were recovered after each discharge. If these traces can be found on a scene of investigation it can support the hypothesis that a 3D-printed firearm was discharged.

Regarding the quantity of big and medium sized fragments, that can easily be noticed by eye and therefore also be collected by hand, it depends on the firearm's damage caused by the ignition of the ammunition. As a rule, it can be stated that the higher the damage on the firearm, the more fragments of those sizes can be found. First, these fragments can be used to reconstruct the object and thus help in identifying the firearm (physical match). Secondly, these

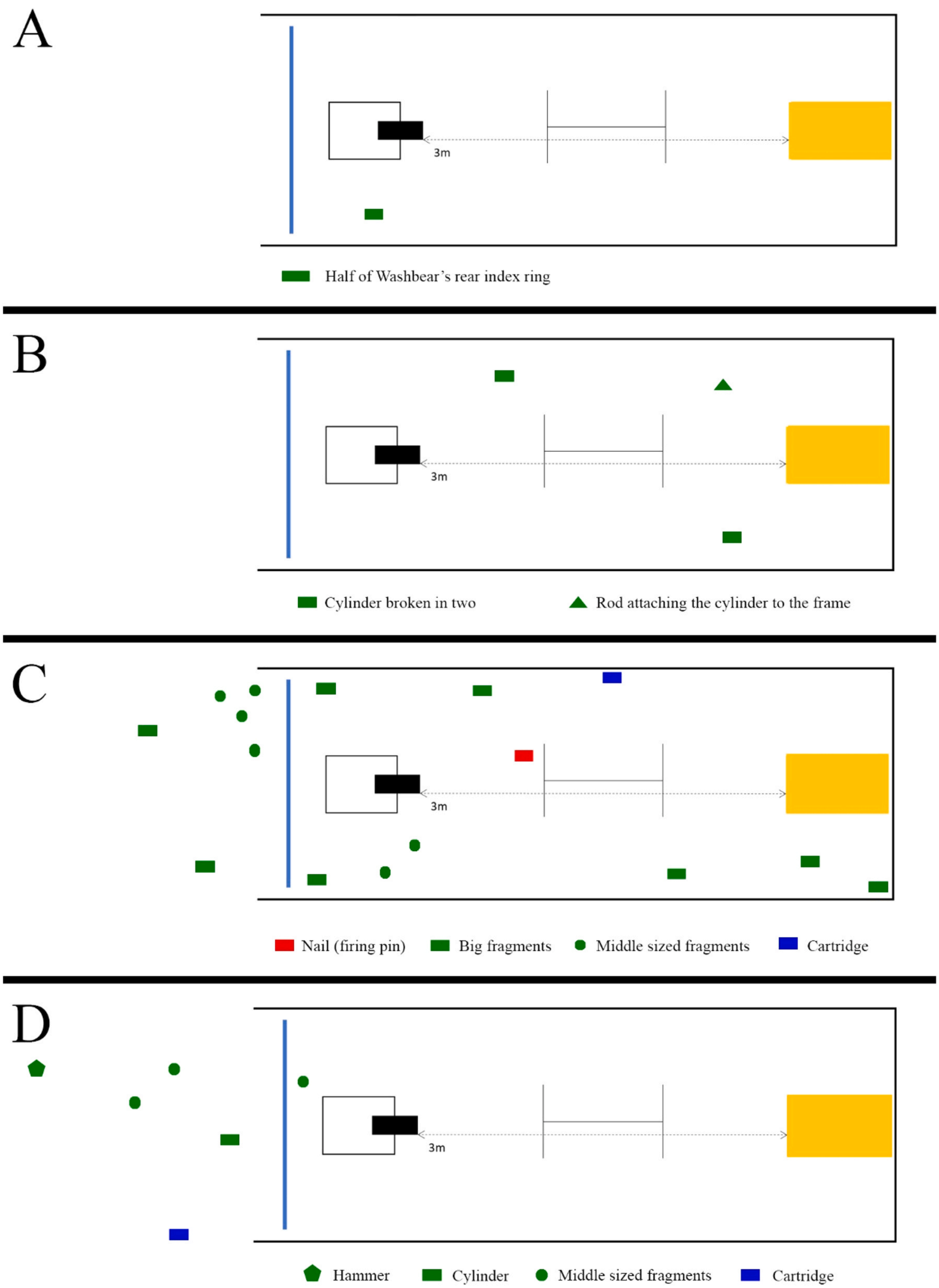

Fig. 4. Distribution of recovered fragments after the discharge of the different 3D-printed firearms: (A) PM422 Songbird and PM522 Washbear, (B) Marvel, (C) TESSA, (D) TREVOR.

fragments contain information about manufacturing conditions that, when determined correctly, provide information about the equipment used and printing parameters set by the user during the preparation of the print. As shown by [8], the printing process may be determined by observing the attributes left on the object. Manufacturing features are defined as the transcription of the printing parameters defined by the user in the Slicer software onto the physical object. As for this project only an ME printer was used, specific attributes of this process were observed. The horizontal layers and single lines extruded through the nozzle are easily observable and distinguishable. Further observations and measurements of the fragments allow us to determine different types and values of printing parameters. For example, the values of the layer height and extrusion width, or the infill pattern and percentage can be determined.

Smaller polymer fragments, that were collected with the adhesive sheet, contain less information about the manufacturing conditions, as their potential decreases when the fragments are of smaller size. Still, it is possible to measure certain attributes, such as the layer height and extrusion width.

Among those smaller fragments, unburnt and partially burnt particles of GSR can be found on the adhesive sheet. Firearms that suffered more damage released more such particles, as the combustion of the propellant powder may be incomplete and imperfect as the firearm explodes. The morphology of these particles can be characterized under a microscope and further (chemical) analysis may help in determining the type of ammunition used.

3.1.3. Elements of ammunition

Among the six discharges, five projectiles reached and penetrated the ballistic soap. Only in the case of the Washbear, the projectile missed the target (ballistic soap) and could not be recovered from the bullet trap set up behind the target. For the five projectiles that reached the target, the velocity was recorded, and the depth and trajectory in the soap were measured. In comparison to studies conducted with the Liberator printed in ABS, PETG (PolyEthylene Terephthalate Glycol-modified) or Nylon and using .380 ACP ammunition, the measured velocities are in accordance to what would be expected of a printed firearm, which means it is greatly inferior to that of a conventional firearm [8,11].

After the discharge, the projectile does not seem to have a stable trajectory, as there were several occurrences in which it was observed that it impacted the soap sideways, instead of being in a frontal position, as it should be with a conventional firearm (Fig. 5). The same phenomenon further influences the dimensions of the cavity. It was also observed that the projectiles began spinning backwards (Fig. 6). The breaking of the barrel combined with the absence of spin could explain the observed behavior of the projectiles. In fact, the parts made from polymer are not as resistant as metallic parts, as used in conventional firearms. Therefore, the polymer suffers from weaker mechanical properties, such as inferior toughness or strength. Some of the 3D-printed firearms had rifled barrels but due to the material's properties it is expected that the rifling was not able to induce a spin to the bullet.

The soap penetration and wounding patterns were also similar to what was recorded in previous studies, seeing that most of the energy of the projectile seems to be transferred at the entrance of the wounding trace [10]. The depth penetration ranges from 3 to 13 cm depending on the ammunition. Considering those observations, we can say that the wounding capacity of ammunition discharged by a F3DP firearm seems greatly inferior to that of classical firearms. Nevertheless, the results have shown that even with inferior penetration values the projectiles can still cause injuries. Since those firearms tend to explode after firing, influencing the projectile's stability during its trajectory, the accuracy and the penetration performance decrease more over larger distances. Therefore, said firearms are more effective over short distances.

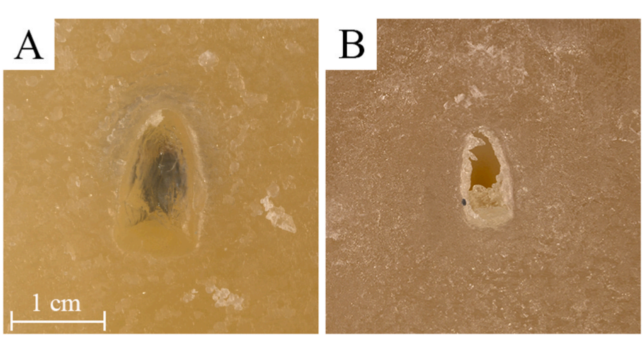

Fig. 5. Appearance of the projectile entry hole provoked by (A) the TESSA with 9 × 19 mm Parabellum ammunition, and (B) the Grizzly with .22 Long Rifle ammunition.

Fig. 6. Cavity in the ballistic soap (side view) and projectile's backwards spin; the bullet was fired with the Songbird in .22 Long Rifle caliber.

Regarding the cartridge cases, it was found that they were stuck in the barrel in four firearms and were only ejected away from it when firing the TESSA or TREVOR. As stated before, these two F3DP firearms suffered the most damage to their integrity. On closer inspection, the cartridges cases showed the same traces of use as shown in previous studies [8,11]. They were either torn, as with the TESSA and Grizzly, or swollen, as with the Songbird, Washbear, TREVOR and Marvel (Fig. 7).

In the case of the TESSA, the cartridge was torn closer to the case-mouth and expelled away from the firearm as the whole firearm exploded. The cartridge case recovered from the Grizzly's barrel was torn in a neat tear all the way from the case-mouth to the case-head while being stuck inside the barrel. The fact that it was not expelled can be explained by the design of the 3D-printed firearm, with the barrel tightly locked in the frame which was not damaged by the discharge. This linear tear may be due to the fact that the thickness of the barrel was sufficient to contain the pressure, not allowing the cartridge to tear in the same way as the ones observed in previous studies and in the case of the TESSA. The other four cartridges were found intact, but slightly swollen. It was easily noticeable in the case of the TREVOR, with a bulge near the rim of the case, while it was rather discreet on the three other firearms Songbird, Washbear and Marvel. The swollen cartridge cases complicated the removing from the chambers as they were tightly trapped and fixed inside them.

Lastly, the two central fire cartridges had their primer cap pierced (TESSA and Marvel), while the rim of the rimfire cartridges was pierced only once on the TREVOR (Fig. 8). This could be explained by the manufacture of the nail used as a firing pin and is a result to be expected when using unconventional and homemade 3D-printed firearms. It is also one of the reasons why none of the firearms were able to discharge successfully on the first try, as this non-printed component is crucial for the proper use of the firearm. Its adjustment and fitting depend on the skill and experience of the manufacturer, and it may prove slightly difficult to manufacture an appropriate firing pin.

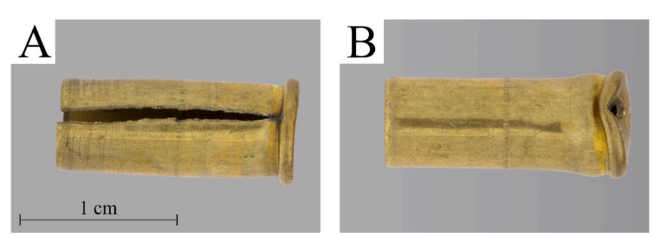

Fig. 7. (A) Torn .22 Long Rifle cartridge case fired with the Grizzly and, (B) swollen.22 Long Rifle cartridge case fired with the TREVOR (the rim is pierced).

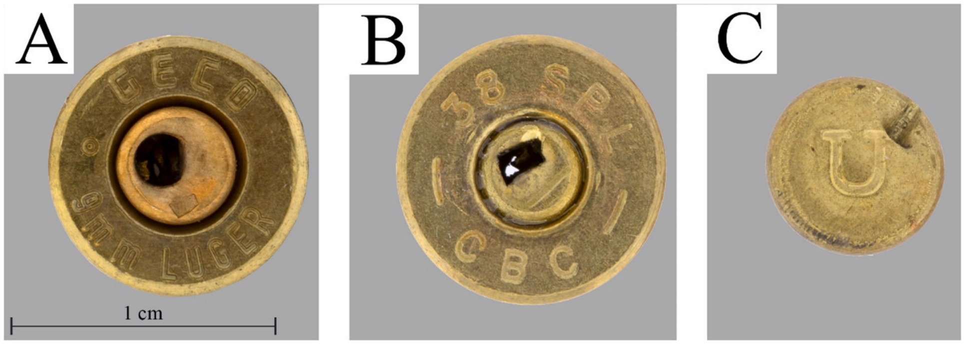

Fig. 8. Pierced primer caps or rim after discharge respectively of (A) TESSA, (B) Marvel and (C) TREVOR.

Since depositions of melted polymer on the cartridge cases and bullets were observed in previous studies, these elements were also examined for such traces [11]. Observations under UV light and wavelengths of 415 nm, 450 nm and 470 nm showed that the PLA used in this project is not luminescent. Nevertheless, melted polymer could still be observed under white light in the form of whitish depositions. For an illustration of such depositions on projectiles and cartridge cases, pictures of a previously published study can be consulted [11]. Quantities of polymer depositions were higher and easier to observe on the 9 × 19 mm Parabellum and .38 Special bullets than on the .22 Long Rifle lead bullets. This is due to the .22 Long Rifle lead bullet's composition which complicated the examination. Melted polymer was mainly present on the base of the bullets, as these parts have most contact with the polymer during their passage through the barrel. Regarding the cartridge cases, melted polymer could also be observed on the body and the case head. They were mainly present around the areas where the cartridge cases were either swollen or torn. In general, the quantity of melted polymer on the cartridge cases was inferior to the quantities observed in previous studies with the Liberator [11]. This means that the examination of said traces must be undertaken with more attention and care.

3.1.4. Traces on the firearms

Through the observation of the fragments shed by the firearms, it was observed that physical matches between different pieces were usually possible. It proved to be relatively efficient in the case of big fragments, considering the morphology of the fracture, and sometimes with small fragments as well. Indeed, it is also possible to rely on the printed framework to support a physical match, with big and smaller fragments altogether. The pressure exerted on the polymer during the discharge may deform the fragments, expel small parts of polymer in the area around the crack or even pulverize some polymer parts, leading to a physical match not perfectly fitting. Nevertheless, by considering the morphology of the surface the reconstructions are still possible and a promising tool in the examination of those pieces. In the example with the Songbird, a small fragment was expelled away from the firearm's barrel which was then collected in the surroundings of the firearm. First a physical match between the two halves of the barrel was confirmed. Subsequently, the small fragment could be physically matched with the gap between the two halves and therefore determining its origin from the barrel (Fig. 9). In this exact case, it was fairly easy to match the fragment with the damaged barrel as only one small fragment was found in the surrounding of the discharged firearm. Such physical matches may prove to be more difficult when the shooting produces a larger number of small fragments in the surroundings.

It was observed that a barrel (Grizzly) and several cylinders (Washbear, Marvel and TREVOR) split in two pieces at the height of the opening of the cartridge case when the ammunition was inserted. This phenomenon may be explained by the localized increase in pressure and diameter at the time of the discharge, thus causing the fracture. The splitting occurred in the horizontal layers and printing direction of the object. In those cases, it was also possible to assemble the two separated parts originating from the same barrel. One way to do this would be, as explained before, to consider the shape of the fracture and the outer framework of the pieces. Since the fractures occur in the horizontal plane of the object, the morphology of these layers is in fact the mirror image of each other's surface. This phenomenon is highlighted in Fig. 10, showing the two parts and their horizontal surface. This type of physical match worked well with the barrel of the Grizzly and the cylinders of the Washbear and Marvel. The cylinder of the TREVOR was more severely damaged by the discharge, resulting in an important projection of small fragments. This limits the physical matching of pieces.

Lastly, each of the six firearms were examined for traces of the cartridge case-head. In the case of the TESSA, a mirror-inverted impression of the case-head's inscription was almost neatly transferred onto the hammer body, which resisted the pressure of the discharge and suffered only minor damage. Said trace is visualized in Fig. 11. If such an impression is present it can inform about the ammunition used and provide investigative information. Same traces could not be observed on any other firearm tested in this project. However, an impression of the outer circle of the head was left on the pieces in contact with the case-head. Observation and measurement of these impressions may inform about the caliber used with the firearm in question.

3.2. General discussion

The printing of the different firearms and their parts was straightforward. The assembly process went relatively well due to the performance of the desktop printer used and mostly only minor post-treatments (e.g., removing supports, sanding) were needed. Regarding the general functionality of the tested firearms, it was asserted that none of them were able to discharge on the first try. Several reasons can be given for this. The fabrication of the firing pins from ordinary nails proved to be complicated and several attempts were necessary to iteratively shape a suitable firing pin for each firearm. Instructions for the manufacture of the firing pin, describing dimensions and shape, were not available for all firearms. Also, for the rubber bands needed to power certain parts (e.g., trigger, hammer), several attempts were needed until the correct choice and number was found so that the firearm could be discharged. In this case, too, the instructions are not always precise. For example, the designer of the Washbear suggested in his instructions that dental rubber bands should be used to power some parts. In some cases, it was even necessary to redesign some blueprints to make the firearm function correctly. Since this project involved simple modifications, they could be processed relatively easily and

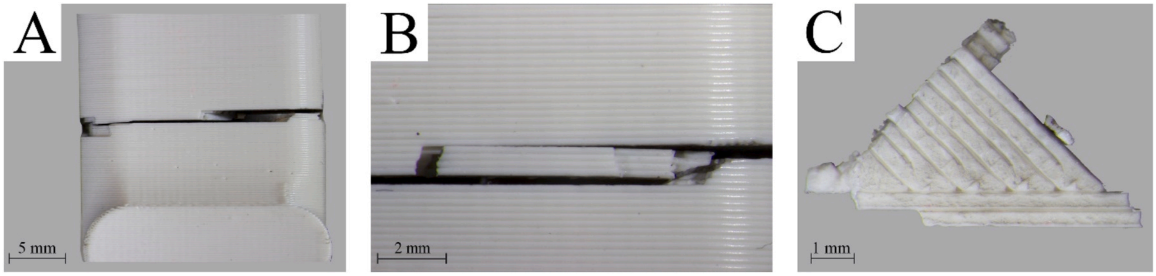

Fig. 9. Physical match between different pieces of the Songbird's barrel, (A) without and (B) with a small fragment. (C) The missing small fragment.

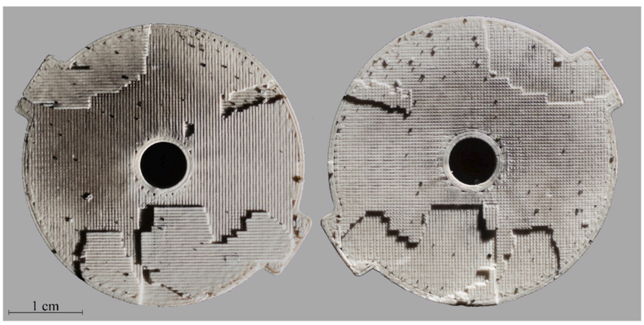

Fig. 10. Physical match supported by the mirroring between the two parts of the Grizzly's barrel. The pieces were photographed with reversed lighting.

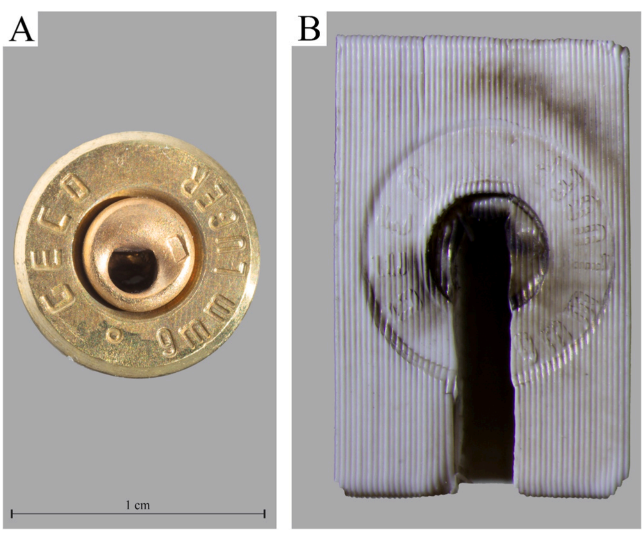

Fig. 11. (A) Case-head of fired 9 × 19 mm Parabellum cartridge fired by the TESSA. (B) Case-head mirror-inverted impression of inscription left on the hammer body of the TESSA (mirror image).

quickly with an appropriate CAD program. However, more complex modifications can be more challenging and time-consuming due to the properties of STL files. Since the surfaces are described from a series of triangles, this can lead to a complex mesh, which can make the editing more complicated. These facts show that the fabrication is not only dependent on the printing equipment used, or the design and blueprints, but also on the user's crafting and manufacturing abilities. Moreover, this demonstrates that trial-and-error methods have to be applied in some cases in order to determine the appropriate configuration. On average, it took about 5 – 10 attempts before the firearm could be discharged. In the case of the Washbear, it took approximately 20 attempts.

After several attempts, all the tested F3DP firearms were successfully discharged which proves that these 3D-printed firearms are actually functional. Simply, it would be wrong to hope for any printed 3D-printed firearm to function as it can be seen on many YouTube videos. As a practical example, many videos of the Songbird are available and a few articles mention test-records about the Grizzly or the Zigzag, which is a former version of the Marvel. On those medias, very few failures of the Songbird and Zigzag are recorded whereas the Grizzly is said to have been damaged only after fourteen shots [13]. Those results did not correspond to what was actually observed in this paper. Since the conditions of manufacture and of use cannot be determined with the available material, reliable statements or explanations of such differences are not possible and only hypotheses can be put forward about them. Such hypotheses include possible reasons that the equipment used (printer, filament, post-processing, etc.) to make the firearm is different or that the use of the firearm, for example different or underloaded ammunition, was carried out differently than in this project.

Moreover, it is important to note with the Songbird and Washbear, the designer specifically noted to not use PLA for printing the firearms, especially the barrel. Despite this, we deliberately used PLA for the printing of firearms in our project. It can be expected that the results might differ when the parts are printed with Nylon or if metallic tubes serving as barrels are added to the firearm. PLA is very easy to print and considered as a user-friendly material that is mainly used in hobbyist printing, whereas the printing with Nylon requires a more sophisticated printer and additional equipment. Nylon offers therefore better mechanical properties (e.g., resistance, toughness) than PLA, which has a lower melting temperature causing it to lose strength quickly with rising temperature but also a poorer durability and lower impact resistance [14]. Although it follows that the choice of material has an influence on the functionality of the firearm, it was decided that the conditions should be the same for all firearms. Comparisons could thus be realized in a simpler way and no additional factor to be considered was included in order to assess the functionality of the firearms. Moreover, the choice of PLA reflects what can be found in real cases, as this material is most commonly used in the private sector. PLA and its improved variant PLA+ are also recommended for printing in 3D-printed firearms circles today.

Then comes the aspect of the potential danger faced both by the shooter and the target. Indeed, of the six firearms, two exploded completely (TESSA and TREVOR), expelling fragments all around the firearm, meaning also in the direction of the shooter holding the 3D-printed firearm. Three other firearms expelled fragments to the front (Marvel), or to both sides (Songbird and Washbear), while only one firearm did not expel anything and did not endure any apparent damage (Grizzly). Although the firearms suffered different levels of damage, each barrel or cylinder broke after just one discharge. Hence, it would at least be necessary to replace those parts to be able to discharge the firearm a second time. This fact reduces the efficiency of the 3D-printed firearm, especially if it is designed to be a revolver (Washbear, TREVOR or Marvel).

Regarding the target, the general outcome was that the bullet's trajectory appears to be unstable. The bullet velocity and its penetration in ballistic soap is also greatly inferior to that of a bullet fired with a conventional firearm. In other words, this means that its apparent efficiency and performance are inferior to that of a classic firearm and further decrease with distance. Regarding the risk of injury, only some basic observations were made in this project. The depths of penetration in the ballistic soap have shown that such firearms can cause serious injuries. Especially at shorter distances, this danger is estimated to be even more serious. The ballistics data obtained in this project are more basic and also present some limitations. For example, the ballistic soaps lacked skin or bone simulants which may affect the results. Further studies are needed that focus on the dangerousness of these firearms so that more data is available on this topic.

The discharge generated typical traces of 3D-printed firearms. Compared to previous studies conducted at the School of Criminal Justice of the University of Lausanne, the same types of traces were collected and analyzed [8]. The cartridge cases were either swollen or torn after the discharge and polymer deposition were observed on the cartridge cases as well as on the bullets. However, pierced primer caps or rims were not observed in the studies about the Liberator and are therefore a new type of trace. Nevertheless, this type of trace is also common to the use of homemade firearms. Regarding the polymer fragments, it is possible to state that the higher the damage on the firearm, the higher the quantity of fragments. Fragments were still collected even in situations where the firearm only suffered minor damage. Further examination of these fragments and their attributes has the potential to provide information about the manufacturing conditions. This type of information can be used in a first stage as investigative information to help in determining what type of material and equipment was potentially used. As soon as reference material is available (e.g., 3D printer, G-Code or any other material necessary for the printing or other 3D-printed objects), the information extracted from the fragments in question can be compared to this material and potentially establish a link between these entities [8].

In cases where traces typical of the discharge of a 3D-printed firearm can be found, investigation and examination strategies need to be adapted with the aim that relevant traces can be identified and collected on a shooting scene and subsequently examined in the laboratory. On the scene of investigation, precautions need to be implemented so that even the smaller fragments can be collected. It would also be useful to draw a sketch of where different traces were found which can help in approximating the shooter's position. In addition, equipment used for 3D printing that may be found on the scene or at a suspect's place must also be collected, as this can be used as reference material. Further examination of the collected traces in the laboratory then helps to extract information from the traces. Physical matches, for example, may provide information about the model of 3D-printed firearm and observation of manufacturing attributes provide information about printing conditions and parameters. Polymer fragments can also be submitted for chemical analysis in order to determine their composition and type of polymer. Several projects have already been carried out in which the analysis of polymer in the context of 3D-printed firearms is described in more detail [5–7]. The aims of the examination are the reconstruction of the event, to provide investigative information about printing conditions, as well as the linking between the traces found on the scene of investigation and the printing conditions and even with the workshop.

Lastly, in some of the firearms, space is included that is intended for metallic parts so that the 3D-printed firearm would comply with the undetectable firearms law in the USA. Adding metallic parts in those spaces would render the firearm legal in some states of the USA but leaving those parts out will have no effect on the functionality. That law being only applicable in the USA, this type of homemade firearm still poses problems worldwide. In countries with strict gun laws, bypassing the law by buying firearms on the black market may be more time consuming and expensive than buying a 3D printer and fabricating a firearm at home. Plans are freely and easily available on the Internet, the designs are increasingly more sophisticated, and designers are making the process of fabrication ever easier by redacting detailed user manuals.

These points show that further studies are still needed in the field of the 3D-printed firearms. In regard to this project, only one firearm of each model was printed and only one discharge was carried out. Further tests should therefore study the intravariability by including more replicas of each model or new printing conditions (e.g., different printing process, printing material, etc.) so that the stated observations may be confirmed or not. Despite this limit, it was possible to demonstrate other models of 3D-printed firearms that had not been studied in detail before. Other research has focused on the Liberator, however, there has been tremendous progress in the field of 3D-printed firearms over the last 10 years, making studies such as the one presented crucial. Initial findings on the performance of new models of 3D-printed firearms as well as observations of the traces allowed us to complete and expand the knowledge gained through previous studies. Future studies are already underway to complement and extend the results presented in this work.

It would also be interesting to evaluate the traces generated after consecutive discharges of the same 3D-printed firearm. As there are dozens of different F3DP and hybrid firearms, subsequent studies may include new models which were not tested so far. Of a more practical aspect, it could be interesting to create a database with printed firearms pieces and study the possibility of scanning fragments of a certain size, retrieved on an investigated scene, in order to find matches (depending on its shape) in the database, allowing one to infer on a group or at best a certain model of 3D-printed firearm.

4. Conclusion

Since the release of the blueprints of the Liberator, the first 3D-printed firearm, by Cody Wilson and his group 'Defense Distributed', numerous new designs of firearms and parts for firearms have been published. The communities with interest in 3D-printed firearms are as well numerous and share their files and information willingly and for free on the Internet. Reports, videos and other documents that can be found on the internet show the potential of these 3D-printed firearms, which are becoming more and more sophisticated and reliable. With the amount of information available on the internet, even ordinary people can produce 3D-printed firearms from home with relative ease. With such homemade production, not only can laws be circumvented, but the state has no knowledge of these F3DP firearms. The large number of designs available and the ease of production poses new challenges to the work of security policy and forensic investigation. Research about 3D-printed firearms in a forensic context is rather rare and detailed studies of the traceology after the discharge of models other than the Liberator are not present. Therefore, this study's aim was to expand the acquired knowledge about the traceology by studying different new models of 3D-printed firearms.

Six F3DP firearms were selected, each printed once with PLA on a Prusa i3 MK3S. Three of the six were revolver-type firearms, namely Marvel, Washbear and TREVOR, and the three remaining were single-shot firearms, namely Songbird, TESSA and Grizzly. Each F3DP firearm was then submitted to a firing-test and discharged only once. None of the firearms could be discharged on the first try and several attempts and modifications were needed before achieving a successful discharge. All six firearms were deemed functional after the tests. Measurements of velocity and penetration in ballistic soap as well as observation of trajectory, showed that their performances were greatly inferior to those expected for classic firearms. Even though the firearms suffered different levels of damage, none could be re-used without switching out damaged and broken parts. The Songbird, Washbear and Grizzly suffered the least damage, but polymer fragments were still projected in the surroundings. The other three firearms suffered more damage resulting in a higher quantity of polymer fragments in the surroundings. Typical traces of a discharge of a 3D-printed firearm were found. The elements of ammunition showed signs of tearing and swelling, and polymer deposition were observed. Pierced primers were observed in three cases which was not observed in former studies about the Liberator. The amount of polymer fragments found in the surroundings depended on the damage suffered by the firearm, but fragments could be collected in every case. Observation and examination of such traces can provide information about printing equipment and conditions which can advance the investigation or establish links between different entities of the investigation such as the workshop.

Further research is needed to assess the variability for each firearm so that it can be evaluated if the findings of our experiments are confirmed and may be generalised. Other hybrid and PKC designs should also be included in such studies. In the future, the additive manufacturing technology as well as 3D-printed firearms will continue to develop and evolve, therefore further studies are important in order to keep pace with developments in this area.

CRediT authorship contribution statement

Aurélie Szwed: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Stefan Schaufelbühl:** Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Alain Gallusser:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Denis Werner:** Conceptualization, Methodology, Formal analysis, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **Olivier Delémont:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

None.

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Appendix

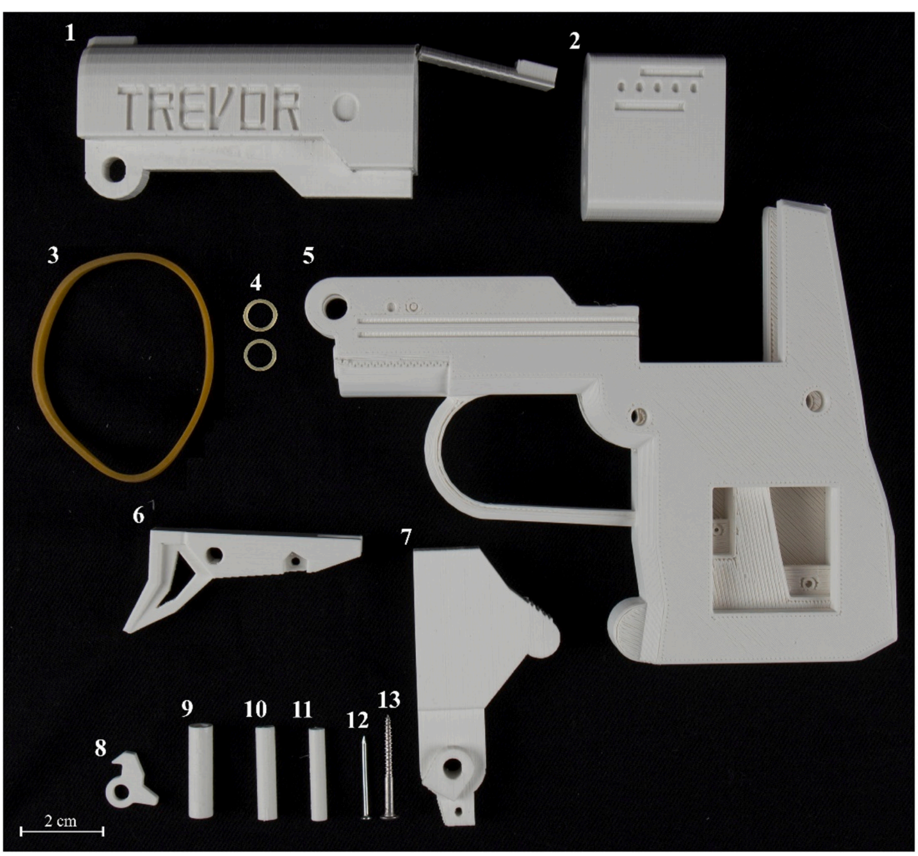
Disassembled 3D-printed firearms

See Figs. A1–A6 here.

Fig. A1. Disassembled PM422 Songbird. Parts 2 (rubber bands) and 4 (firing pin) are not 3D-printed.

1: Frame
2: Dental rubber band
3: Cylinder rod
4: Trigger
5: Grip
6: Scar pin
7: Trigger band retainer
8: Firing pin retainer
9: Nail, firing pin
10: Cylinder
11: Rear index ring
12: Striker
13: Guide rod
14: Grip pin
15: Sear
16: Grip cap

Fig. A2. Disassembled PM522 Washbear. Parts 2 (dental rubber bands) and 9 (firing pin) are not 3D-printed.



1: Barrel
2: Cylinder
3: Rubber band
4: Dental rubber band
5: Receiver
6: Trigger
7: Hammer
8: Barrel lock
9: Barrel pin
10: Hammer pin
11: Trigger pin
12: Nail, firing pin
13: Screw

Fig. A3. Disassembled TREVOR. Parts 3 and 4 (different rubber bands), 12 (firing pin) and 13 (screw) are not 3D-printed.

Fig. A4. Disassembled Grizzly. Part 12 (firing pin) is not 3D-printed.

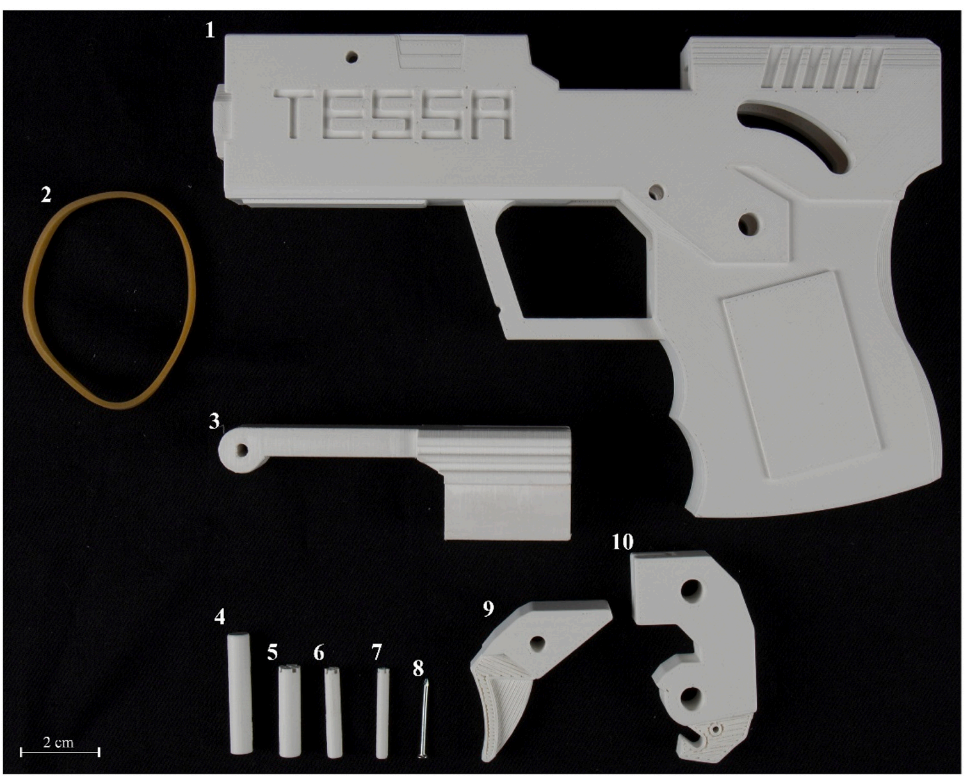


Fig. A5. Disassembled TESSA. Parts 2 (rubber band) and 8 (firing pin) are not 3D-printed.

1: Cylinder
2: Frame
3: Grip
4: Cylinder nut
5: Cylinder rotation pin
6: Hammer
7: Rubber bands
8: Firing pin spring
9: Nail, firing pin
10: Grip screws
11: Trigger screw and bolt
12: Cylinder bolt
13: Trigger guard
14: Trigger
15: Frame cap
16: Block

Fig. A6. Disassembled Marvel. Part 7 (rubber bands) and parts 8 through 12 (spring, firing pin and screws) are not 3D-printed.

After the discharge

See Figs. A7–A12 here.

Fig. A7. PM422 Songbird, after discharge.

Fig. A8. PM522 Washbear, after discharge.

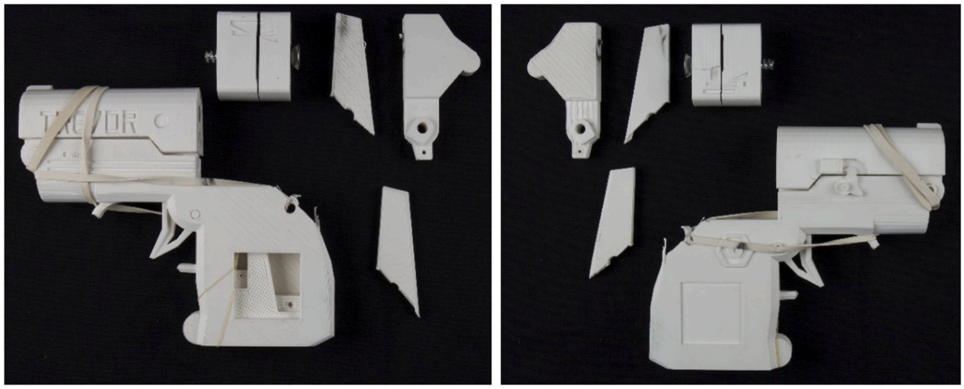


Fig. A9. TREVOR, after discharge.

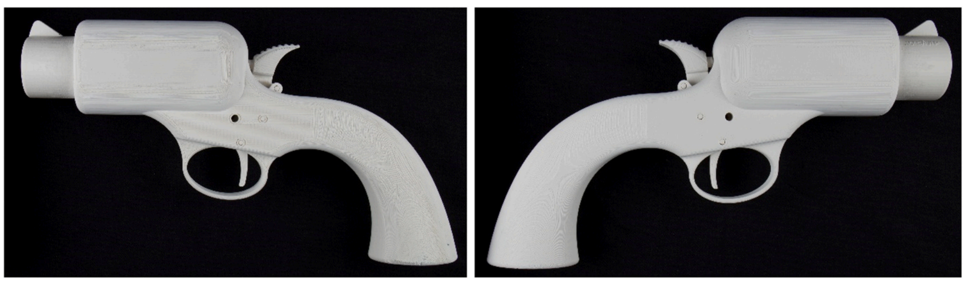


Fig. A10. Grizzly, after discharge.

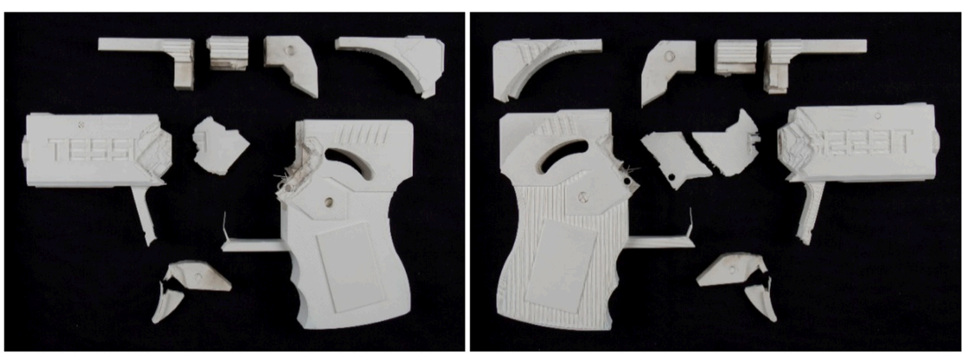


Fig. A11. TESSA, after discharge.

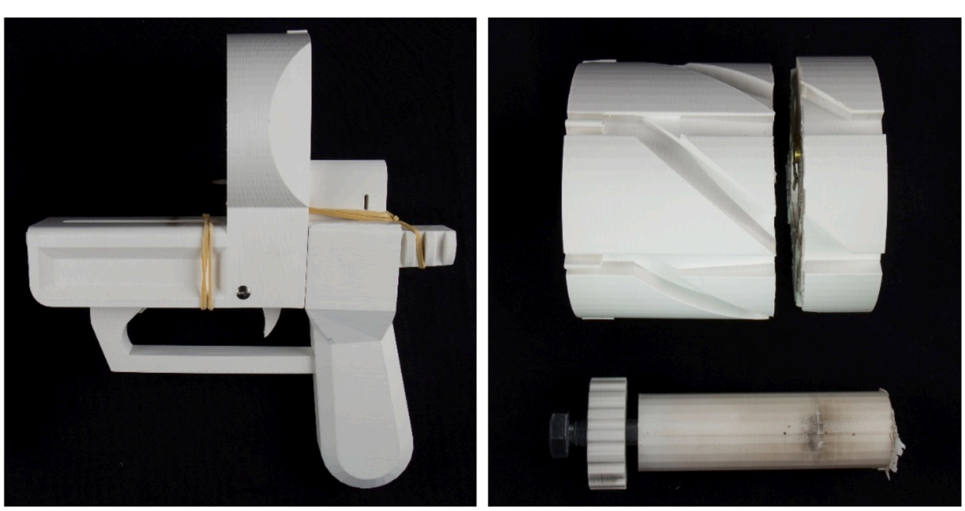


Fig. A12. Marvel, after discharge.

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