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Utilization of Recycled Filament for 3D Printing for Consumer Goods

Alexa Peterson

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Project Summary

The 3D printing market has been used in a wide variety of manufacturing industries including textile and apparel. Many consumers can now own a personal 3D printer at home for recreational printing. There are even websites dedicated to 3D printing patterns made by consumers. However, the materials used in the 3D printing process pose a problem for the environment due to their plastic-based nature. 3D printing is a layered process with each layer being printed depending on the layer below it for strength and stability. During the 3D printing process, great amounts of waste are produced as a result of printing errors that, having occurred, cannot be reused. This waste is plastic based and therefore does not readily biodegrade. Using 3D printing filament created from recycled materials (i.e. plastic bottles) could transform the waste into new re-useable materials which ultimately could reduce the harmful effect of plastic products on the environment over time. One such plastic product is plastic instrument mouthpieces. The current plastic mouthpieces on the market are not created using recycled plastics, so when they break they only contribute to the plastic waste in landfills. Therefore, the study focused on creating functional 3D printed mouthpieces from rPETG filament (Recycled Polyethylene Terephthalate Glycol-modified filament) for the University of Arkansas Hogwild Band brass players to be used during performances. A total of 29 mouthpieces were created for trumpet, trombone, and tuba players in the band and were utilized for the 2020 Hogwild season. Participants were then asked to share their feedback about the performance of the mouthpieces for the final part of the study.

Introduction

The apparel industry is always looking for new, innovative ways of producing garments, accessories, and products for the market. 3D printing technologies are used by numerous fashion retailers and designers to develop samples, manufacture products, and produce customized products for consumers (Hindman, 2013). It is widely known that 3D printing has a significant impact on the garment supply chain by reducing times in production and distribution (Huang, Liu, Mokasdar, & Hou, 2013; Sun & Zhao, 2017). A study about the production of footwear through 3D printing used a combination of 3D design and ergonomics to build a 3D printed shoe for future consumers to use, or even print from their own home (Ghodsi, 2015).

On the other hand, the 3D printing process creates a great volume of waste. It is estimated that 3D printer filament usage will produce a 3D printing waste volume of 8 million kilograms in 2020 (Toor, 2019). 3D printing happens in layers. These layers stack on top of each other and depend upon the previous layer for stability and strength. If at any point during the printing process there is an error or the filament does not print as it should, the entire piece must be scrapped. This 3D printing waste poses a problem to the waste stream, as most 3D printing filament is plastic-based and therefore does not readily biodegrade. The amount of wasted material could be compounded as the 3D printing method becomes more widely utilized. There are now desktop 3D printers that consumers can possess in their own homes. Whereas companies have not yet found sufficient ways to reduce the waste in 3D printing processes, some companies are recycling failed filament or other plastic-based objects (e.g., plastic water bottles) to useable filament. As such recycling efforts may combat the 3D printing waste issue (Toor, 2019), it is important to explore eco-friendly filament options that can be easily adopted by 3D printer users.

This study focuses on testing filament from recycled water bottles, known as rPETG filament. When 3D printing filament is extruded from a recycled product it tends to lose some strength in comparison to pure 3D printing filament. In one study, the chemical dopamine was used to strengthen the polymers of the new, recycled filament (Zhao, Hwang, Lee, Kim, & Kim, 2018). Since dopamine readily absorbs onto any surface with self-polymerization, the aqueous form was used and synthesized via oxidative polymerization to coat the new filaments. The researchers discovered that the tensile tests of the improved recycled filaments were closer to that of the original filament than the non-strengthened version. Another recent study (Reich, Woern, Tanikella, & Pearce 2019) reported that using fused particle fabrication in the extrusion process could be a potential to strengthen the filament even further. Both studies suggested that the tensile strength of the parts manufactured from the recycled filament was comparable to the results of commercial filament printed on both desktop and large-format 3D printers.

The purpose of this study was to create a functional product using a filament made from recycled plastic bottles that were extruded into a filament form for 3D printing. The current study consists of two parts. First, 29 3D printed mouthpieces were developed using rPETG filament for the Hogwild Band brass players to use at the University of Arkansas. The mouthpieces were created for trumpet, trombone, and tuba players in the band and were utilized for the 2020 Hogwild season. Second, players who used the 3D printed mouthpieces were asked to report their experiences regarding the performance of the mouthpieces. Therefore, findings of this study revealed whether the 3D printed mouthpieces made from eco-friendly filament were strong enough to withstand the process of not only being used to make music, but the physical movements band members perform during events. This study made one step to solve the plastic waste crisis through reducing waste generated from 3D printing and provide a service to the band community.

Literature Review

With the increased use of 3D printing technology becoming the norm, the logical next step is to find a way to make 3D printing more sustainable by finding a way to decrease the amount of waste produced during the printing process. In a study conducted by Daya (2017), sustainability was shown to be a low consideration with industry professionals when making decisions about 3D printed products. Daya (2017) reported that most industry professionals make their business decisions based on finances and time constraints, despite caring about the topic of sustainability as individuals. Daya (2017) stated that a Life Cycle Assessment, an approach by industry professionals to assess and create more sustainable products, costs anywhere between $10,000 to $60,000 and takes up to three months to complete, which does not include the additional $15,000 hazard assessment per chemical for the new material. Thus, companies do not have any incentive to provide a change in materials unless pressured by consumers.

Recycled 3D printed filament takes time and effort to reconstruct to mimic the original product. Per Zhao et al. (2018), the recycling of polymeric materials causes degradation of the mechanical properties, indicating that recycled 3D printing filament may not be as strong as its original counterpart. Zhao et al. (2018) sought to combat this by adding polydopamine to waste filament to strengthen the new, recycled filaments. Increased strength makes recycled filaments a viable option in the market. However, more research and testing needs to be done to determine if the products produced from these recycled filaments hold up as well as the original product under stress, such as the stress of being played in a musical instrument.

Musical instruments are not only a commodity, but an expensive one at that. Per Kantaros and Diegel (2018), the increase in the standardization of musical instruments requires advanced levels of manufacturing and specific tools that can only be provided by highly trained craftsmen. It is important to test new methods of production that not only take less time, but also require fewer resources and less labor to advance the market. While additive manufacturing, otherwise known as 3D printing, was used for musical instruments in Kantaros and Diegel's (2018) study, manufacturing from recycled 3D filament has not been extensively investigated. Expanding the potential uses of recycled filament to create useful products is important to increasing the sustainability of the 3D printing industry.

Development Plan

Following is the development plan by which this creative project was guided:

1. After receiving IRB approval (IRB protocol number 2001244099 approved 3/3/2020; Appendix A) participants signed an informed consent for and were recruited to fill out a survey asking them several questions as follows (Appendix B):
    a. Name
    b. Years in the Hogwild Band
    c. Instrument
    d. Have you ever used a plastic mouthpiece for your instrument in the past?
    e. Would you be willing to participate in this study by performing on a 3D printed mouthpiece for all or part of the Spring 2020 season of Hogwild?
    f. If yes, what size mouthpiece do you currently use?
2. After surveying the participants, rolls of recycled PET filament re-manufactured from transparent bottles were then purchased from 3dfuel.com.

3. 3D model files were found on Thingiverse.com for 1.5C, 3C, and 7C trumpets mouthpieces, as well as trombone, mellophone, and tubas. These files were converted from .stl file types to g-code file types for printing using Ultimaker Cura.
4. The process of printing the mouthpieces from recycled 3D printer filament then began.
5. Upon completion, the mouthpieces were distributed to the participants and they performed on them for the Spring 2020 Hogwild season.
6. Upon the conclusion of the season there was a follow-up survey, asking some of the following questions to assess the performance of the 3D printed from recycled filament mouthpieces (Appendix C):
    a. Instrument
    b. Years in the Hogwild Band
    c. Have you ever used a plastic mouthpiece for your instrument in the past?
    d. How often did you use your 3D printed mouthpiece?
    e. Did the mouthpiece last the entire season?
    f. If it broke, when did it break?
    g. Did you enjoy playing on the 3D printed mouthpiece?
    h. What, if anything, would you change about the mouthpiece if you could?

Design Process and Creative Works

Product testing for the 3D printed mouthpieces from recycled filament was conducted in February and March 2020 using a varied assortment of mouthpiece sizes for different instruments. Upon signing the informed consent forms, participants requested their preferred size and instrument for printing purposes. Participants were acquired from the University of Arkansas Hogwild band, a pep band that performs at all sporting events except football. The 29 participants consisted of nineteen male and ten female students ranging from freshman to senior in the brass section of the band, which included twelve trumpets, seven mellophones, seven trombones, and two tubas. There were no baritone participants. Nine participants were participating in Hogwild for the first time, eight for two years, eleven for three years, and one had participated in Hogwild for all four years of college. A roll of transparent recycled rPETG filament, which was re-manufactured from transparent bottles (1.75mm), was ordered from 3dfuel.com for use in creating the mouthpieces. Using the website www.thingiverse.com, a free 3D print file website where consumers upload their own custom patterns for people to use, 3D print files were found for all the mouthpiece sizes. The Thingiverse files come in a .stl file type, which meant that the files had to be converted prior to printing because the 3D printer requires g-code to print. These files were downloaded into an app called Ultimaker Cura in order to optimize them into the proper g-code file type to be inserted into the printer as shown in Figure 1. Ultimaker Cura allows the user to change the print settings prior to printing. The user can change setting such as infill, what kind of support for the print they want used, as well as change the orientation and size of the 3D model. The trumpet participants requested four 1.5C, seven 3C, and one 7C mouthpieces, while the mellophones, trombones, and tubas requested to just have a mouthpiece that matched their instrument as they did not have a preference on size. The mouthpieces were then sanded down around the rim of the mouthpiece using sixty-grit sandpaper to remove any sharp or rough edges and smoothed out using 220-grit sandpaper. Twenty-nine mouthpieces were created in total and distributed among participants. The participants were instructed to use the mouthpieces at as many or as few games as they desired. On March 24th, 2020 a final survey was sent to participants who used the 3D printed recycled filament mouthpieces to receive feedback for future testing.

Printing Process

After purchasing a filament created from recycled plastic materials the recycled filament was printed into mouthpieces for the Hogwild Band at the University of Arkansas. The Hogwild Band is an on-campus organization that performs at sporting events such as volleyball, men's and women's basketball, as well as tennis and gymnastics. Metal mouthpieces are expensive; the smallest trumpet mouthpiece can cost about $50 in retail stores, and they are always in high demand. Metal mouthpieces are durable and weather resistant, they do not rust in the rain or melt in the heat, though in the winter they get extremely cold. In recent years, mouthpiece retailers began offering plastic based options for brass players at lower prices as an alternative to metal mouthpieces. The Wedge Mouthpiece Company offers two different types of plastic mouthpieces, Delrin and Acrylic. Delrin is softer than the Acrylic mouthpieces, is strong and resistant to chemicals, bounces when dropped, and has a dark sound. Acrylic is far more brittle and can crack if dropped on a hard surface as well as if it is exposed to chemicals, which means it cannot be cleaned with most mouthpiece cleaners and has a sound more akin to a brass mouthpiece ("Plastic or Brass?", 2020). Current commercial brass mouthpieces are also weather resistant, but have the added benefit of resisting the cold better than metal mouthpieces at the expense of durability. These plastic options come in many different sizes to suit all players needs and preferences as well. One of the benefits of 3D printing mouthpieces is that they can be made in any size the musician needs for a fraction of the cost as long as there is a 3D model available for that size.

The printer used was a NWA3D A5 desktop machine as shown in Figure 2. This printer had a build volume (length x width x height) of 5.9 x 4.9 x 3.9" with a nozzle size of 400 microns and a maximum temperature of 464 degrees Fahrenheit. A roll of transparent recycled

PET filament re-manufactured from transparent bottles (1.75mm) from 3dfuel.com was purchased for use in creating the mouthpieces. The filament required printing at a temperature of 375 degrees Fahrenheit at 100% infill to ensure strength and durability of the mouthpieces. The bed of the 3D printer was leveled to prevent misalignment of the prints before printing could begin. Using the website www.thingiverse.com, a free 3D print file website where consumers upload their own custom patterns for people to use, 3D print files were found for all the mouthpiece sizes. These files were then downloaded into an app called Ultimaker Cura in order to optimize them from a .stl file into the proper g-code file to be inserted into the printer. Four 1.5C trumpet, seven 3C trumpet, one 7C trumpet (Figure 3), seven mellophone, nine trombone, and two tuba mouthpieces were printed for 29 mouthpieces in total. The printing process took approximately a month to complete in total as each mouthpiece took anywhere between two hours for the trumpet and mellophone mouthpieces to six hours for the trombone and tuba mouthpieces to complete. During this process, a few errors occurred and therefore scrap waste was produced that could not be reused. Due to the layered nature of 3D printing, each mouthpiece had to have the rim sanded after printing completion. All the mouthpieces were extremely rough and sharp around the rim of the mouthpiece where the printing base started. Sixty-grit sand paper was used in order to remove the bulk of the roughness, then 220-grit sandpaper was used to soften the plastic of the mouthpieces and finish the sanding. Acetone was then poured into the mouthpiece shaft to remove any extra fibers created when the nozzle moved during the printing process. The mouthpieces were then rinsed thoroughly and sat unused for a few days to give the acetone time to wear off. After all the mouthpieces were printed, sanded, and cleaned they were distributed to all 29 participants for testing through the end of the season at the participants' discretion.

Participant Evaluations

Participants were instructed to use their 3D printed recycled filament mouthpieces as often or as little as they desired through the 2020 Hogwild season, the testing period being during February and March 2020. After the season concluded at the end of March 2020, participants who had signed the informed consent form received a follow up email requesting feedback on their 3D printed mouthpieces. Of the 29 participants, 22 of them had never played on a plastic mouthpiece prior to this study. Six had prior experience with a plastic mouthpiece though these were commercially made, not a 3D printed option. Participants were then asked how often they played on their 3D printed from recycled filament mouthpieces. One participant played on their mouthpiece every game, four participants played on their mouthpiece at most games, and 23 participants played on their mouthpieces at a few games. No participants opted to never play on their 3D printed mouthpiece. One of the most telling questions asked was if the participants' mouthpieces lasted the entire Hogwild season. Of the 29 participants, 26 participants had a mouthpiece that lasted the entire season, while three mouthpieces broke before the end of the season. All three participants with a broken mouthpiece had it break in the same structural location on the mouthpiece. The cup of a mouthpiece is the place where the players' lips meet the mouthpiece and buzzing occurs to produce sound, and the shaft of the mouthpiece is the part inserted into the physical instrument. The participants' mouthpieces broke where the cup of the mouthpiece and the shaft of the mouthpiece met (Figure 4). These three participants reported their mouthpieces fell from a high place and landed on a hard surface and did not break during a performance. The area where the cup and the shaft meet is a structurally thin area as it is the narrowest part of the mouthpiece and therefore has the least structural support, and it was anticipated that this is where the mouthpieces could potentially break, so for only three to break was considered a success. More testing, however, with a larger sample and over increased time would be necessary to further evaluate the structure. Additionally, more testing is needed to assess whether the mouthpieces would stand up to the temperature fluctuations encountered during marching band season. Participants were also asked if they enjoyed their experience playing on their 3D printed recycled filament mouthpieces. The participants were split, 15 saying they did enjoy their experience and 14 stating that they did not. For those who did not enjoy their experience, three main issues were reported. The most common reason the participants did not like the mouthpieces was that the product itself was too rough. 3D printing occurs in layers that can be sharp, especially around edges such as where the players' lips make contact with the mouthpiece. Participants noted that they could not play on the mouthpieces for an extended period of time due to the discomfort caused by the roughness of the mouthpiece. The mouthpieces were all sanded before participants received them, however most if not all participants stated that the sanding was insufficient to mitigate the sharpness and something else needed to be done in order to make the mouthpieces more comfortable on their lips for playing purposes. Another reason participants did not enjoy their mouthpiece was that it was reportedly the wrong shape. When 3D printing, the base of the 3D print is always very flat. This was an issue for many participants because mouthpieces are normally curved on the rim and many of the participants did not enjoy the way the flat brim felt on their lips. The mellophone players especially disliked the shape as the brim of their 3D printed mouthpieces was extremely wide compared to their usual mouthpieces and it completely changed the way they had to play their instruments while lowering many of their ranges from their normal abilities. Another complaint about the 3D mouthpieces was related to tone quality. Partly due to the shape issues, the tone quality of the mouthpieces was different from many participants' normal tone qualities. The tone was described as “darker” than their normal brassy pep band tone, which affected the way the band sounded slightly. Tuning issues were noted as well, which could be fixed on the participants’ instruments but was still a difference noted between a metal and a 3D printed mouthpiece. Tuning is especially important to note as it can alter the way the entire band sounds if even one person is not in tune with the rest. For those participants who did enjoy their mouthpieces, they said if their mouthpiece was improved with increased sanding, better shape, and a better tone quality, they would play on it just as often as their metal mouthpieces.

Conclusion and Discussion

The results of this study indicate that the 3D printed recycled filament mouthpieces are not an exact replacement for metal or even commercially produced plastic mouthpieces. While providing a cheaper option, metal mouthpieces are still the preferred product on the market today. The 3D printed mouthpieces had structural issues where the shaft and base of the cup meet and the plastic was thinner due to the shape of the mouthpiece. This caused breaks in three mouthpieces that rendered the mouthpiece unplayable. Over time, this could lead to increased replacement rates of the 3D printed mouthpieces in comparison to metal and commercially produced plastic mouthpieces. Additionally, the printed mouthpieces were not as comfortable to play on as commercially made metal and plastic mouthpieces, which makes players less likely to purchase 3D printed mouthpieces as an alternative to the current commercial options. In the future, improvements could be made to these 3D printed recycled filament mouthpieces to make them more desirable to brass players as a commercial mouthpiece option. More intense sanding of the mouthpieces is recommended to smooth out the layers around the brim of the mouthpieces. Additionally, an acetone bath followed by a clear coating would potentially smooth out the mouthpieces to current commercial standards. Acetone dissolves the outermost layer of the filament, therefore removing the ridges created during the 3D printing process and smoothing the outer texture. A clear coat is recommended to keep air from seeping out of the slight gaps between layers during players performances. Rendering 3D models of current commercial mouthpieces would also be recommended to ensure the mouthpieces are the correct size and shape for all players using an industry standard. If commercial manufacturers produced these models the future for 3D printing mouthpieces would have the potential to be standardized between all mediums of production.

This study was limited by two main factors and may not be generalizable to a wider audience. The study was limited to 29 participants and the mouthpieces were only used over a two-month period. The ability of the mouthpieces to retain their strength and performance over longer periods of time and under harsher conditions, such as marching band, are unknown. Marching bands practice in both intense heat and cold and temperature testing should be conducted to assess the viability of 3D printed mouthpieces from recycled filament as an outdoor option. Further, the willingness of band members to sacrifice tone quality even if the sharpness and shape of the mouthpiece were improved is unknown. Additionally, band director approval and willingness to adopt a different product would need to be assessed and tested to determine the viability for mass production as many directors prefer all players to perform on metal mouthpieces. Despite the limitations of the study, this project does identify the need to find creative solutions for reusing 3D printing waste filament to minimize the waste going into landfills. Additionally, this project identifies the need for manufacturers to consider providing commercial 3D models to consumers for consistency between prints. While this is but one example of a potential reuse of the recycled filament, many other options should be explored not only in a band setting, but other sectors of production as well.

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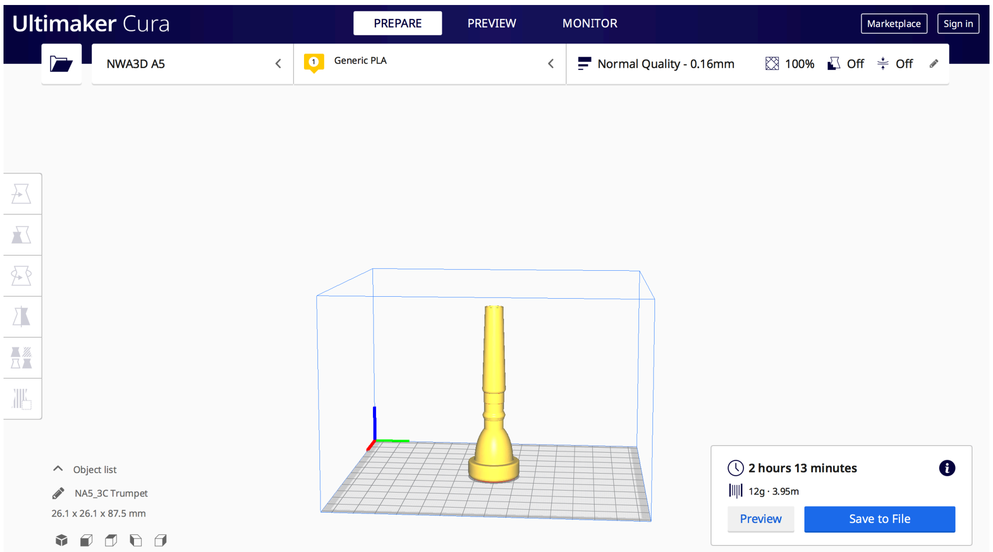
Figures

Figure 1

3D Model for 7C Trumpet Mouthpiece off Thingiverse sliced into Ultimaker Cura with 100% Infill.



Note. Displays the time and printing settings to the right with a visual of the finished product in the middle on a display of the build plate of the printer selected (NWA3D A5).

Figure 2

NWA3D A5 Printer Used for all Printing Throughout the Study

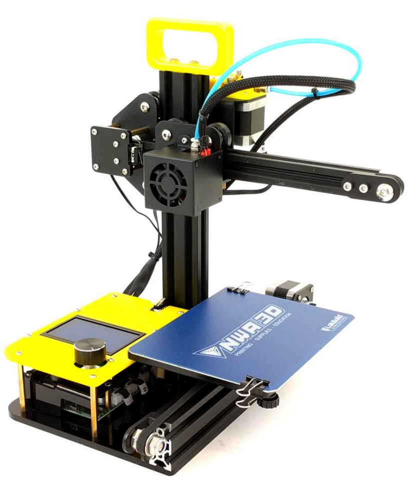


Figure 3

7C Trumpet Mouthpiece Printed Using rPETG Filament to be Played on by a Participant

Figure 4

A Broken Trumpet Mouthpiece after Falling from a High Place.

Appendix A

IRB protocol number 2001244099 approved 3/3/2020

UNIVERSITY OF ARKANSAS

To:	Lisa S Wood AGRI 105A
From:	Douglas James Adams, Chair IRB Committee
Date:	03/03/2020
Action:	**Expedited Approval**
Action Date:	03/03/2020
Protocol #:	2001244099
Study Title:	Utilization of recycled filament for 3D Printing for Consumer Goods
Expiration Date:	02/06/2021
Last Approval Date:	

The above-referenced protocol has been approved following expedited review by the IRB Committee that oversees research with human subjects.

If the research involves collaboration with another institution then the research cannot commence until the Committee receives written notification of approval from the collaborating institution's IRB.

It is the Principal Investigator's responsibility to obtain review and continued approval before the expiration date.

Protocols are approved for a maximum period of one year. You may not continue any research activity beyond the expiration date without Committee approval. Please submit continuation requests early enough to allow sufficient time for review. Failure to receive approval for continuation before the expiration date will result in the automatic suspension of the approval of this protocol. Information collected following suspension is unapproved research and cannot be reported or published as research data. If you do not wish continued approval, please notify the Committee of the study closure.

Adverse Events: Any serious or unexpected adverse event must be reported to the IRB Committee within 48 hours. All other adverse events should be reported within 10 working days.

Amendments: If you wish to change any aspect of this study, such as the procedures, the consent forms, study personnel, or number of participants, please submit an amendment to the IRB. All changes must be approved by the IRB Committee before they can be initiated.

You must maintain a research file for at least 3 years after completion of the study. This file should include all correspondence with the IRB Committee, original signed consent forms, and study data.

cc: Alexa Lynn Peterson, Investigator

Appendix B

Survey sent to participants to collect data in order to produce mouthpieces for participants.

3D Printed Mouthpiece Survey

This survey is in conjunction with the completion of an honors thesis. Your responses will be recorded and a 3D printed mouthpiece will be created for you should you opt to participate in this study. THIS SURVEY IS FOR BRASS PLAYERS ONLY. Please answer all questions truthfully.

* Required

1. Email address *

2. Name *

3. Years in the Hogwild band (NOTE this is NOT your class. For example, if you are a senior but this is the first time you are in the Hogwild band you would select "1" as your answer) *

   Mark only one oval.

   - 1
   - 2
   - 3
   - 4
   - 5+

4. Instrument *

5. Have you ever used a plastic mouthpiece for your instrument in the past? *

Mark only one oval.

- Yes
- No

6. Would you like to participate in this study by performing on a 3D printed mouthpiece for all or part of the Spring 2020 season of Hogwild band? *

Mark only one oval.

- Yes
- No

7. If you answered yes to the previous question, what size mouthpiece do you currently use? (If you answered no, please put NA) *

____

Appendix C

Post survey sent to participants following the testing period to collect data regarding performance of 3D printed mouthpieces.

3D Printed Mouthpiece Survey

This survey is in conjunction with the completion of an Honors thesis and is for research purposes. Please answer all questions truthfully and completely.

* Required

1. Email address *

2. Instrument *

3. Years in the Hogwild band (NOTE this is NOT your class. For example, if you are a senior but this is the first time you are in the Hogwild band you would select "1" as your answer) *

   Mark only one oval.

   - 1
   - 2
   - 3
   - 4
   - 5+

4. Prior to this study, had you ever used a plastic mouthpiece in the past? *

   Mark only one oval.

   - Yes
   - No

5. How often did you play on your 3D Printed mouthpiece? *

Mark only one oval.

- Every Hogwild event
- Most Hogwild events
- Few Hogwild events
- Never

6. Did your 3D Printed mouthpiece last the entire season? *

Mark only one oval.

- Yes
- No

7. If not, when did it break and where on the mouthpiece broke? (ex. at the base of the shaft and the cup). If it did not break please put "NA" *

8. Did you enjoy playing on your 3D printed mouthpiece? *

Mark only one oval.

- Yes
- No

9. In your opinion, what improvements should be made in the future to make the mouthpieces more enjoyable and practical to play on? *