EarBloom: A Bio-Inspired Intersection of High-Fidelity Hearing Protection and Fashion Technology

Kayla Youhanaie[1], Tanya Vidhun[2], Bryan Mui[3] and Yin Yu[4]

[1]Oaks Christian School
[2]Valencia High School
[3]Dougherty Valley High School
[4]Advisor, University of California Santa Barbara

ABSTRACT

Noise pollution has become an increasingly prevalent issue due to audio digitization in the modern world and can cause permanent damage to the ear. However, currently available hearing protection devices distort sound attenuation and are unpopular because they lack comfort and aesthetic appeal. Soft robotics enable new possibilities for morphological hearing protection that, when integrated with fashion, offer a modern and artistic solution. In this paper, we present EarBloom as a solution to combat hearing damage. Inspired by the natural blooming of a flower, EarBloom's folding actuation and high-fidelity chambers were designed and tested in 3D modeling software and utilize electrical stimuli to protect the ear automatically. EarBloom is an innovative, soft-robotic approach to hearing protection that integrates automatic protection, uniform attenuation, and aesthetic appeal.

Introduction

Over the past century, advancements in sound output devices and appliances have exposed humans to increasingly loud sounds, ranging over 120 decibels (dB) in dangerous settings. Noise can be disruptive to basic communication and people's daily lives. Urbanization of cities specifically introduces more unwanted noise due to construction and busy areas such as airports. Unwanted noises put individuals at a greater risk of Noise Induced Hearing Loss, tinnitus, sensitivity, and other complications ("Loud Noise Can Cause Hearing Loss"). As a result, long-term hearing damage has become an increasingly prevalent health and wellbeing threat to all individuals, especially those with predisposed sensitive hearing conditions and individuals working in high-risk professions such as construction, airport settings, and the music industry.

Current wearable ear protection technologies include earplugs, ear muffs, and noise-canceling headphones ("Choose The Hearing Protection That's Right For You"). These products aim to reduce the damage noise can have on ears. However, these protection options, especially commercial earplugs, often cause discomfort and distorted attenuation across the ear (Samelli). As a result, common earplugs are ineffective at evenly reducing noise. Custom-fitted, high-fidelity ear plugs are typically more expensive than their over-the-counter counterparts (Goodwin). The improper insertion of the hearing protection device into the ear can also lead to inadequacy, further discomfort, and potentially long-term injury if inserted too far into the ear canal. Additionally, users experience a delayed reaction time to insert their hearing protection device upon hearing a sudden, loud sound. This delay poses another challenge in effectively protecting the ear and hinders the overall popularity of these forms of hearing protection.

To address these limitations, we propose EarBloom, an effective and aesthetic solution to combat hearing damage. EarBloom's automatic actuation process uses electrical stimulus to close and cover ear openings in response to loud sound levels. We also integrated an automatic inflatable earplug into the design for extremely loud and sudden emergency scenarios. In addition, our design is implemented on the external ear cuff area so as to avoid direct contact and intrusiveness of the inner ear that triggers discomfort. EarBloom is inspired by the opening and closing of blooming flower petals and the design of peacock feathers to provide an artistic physical appearance. We developed several designs of EarBloom and aimed for comfort, fashion, and uniform attenuation across all sounds. EarBloom utilizes recent advancements in wearable sensors, soft material, and electrical stimuli along a conductive filament to provide an innovative solution to noise pollution. This paper presents our process of (1) digitally modeling EarBloom and evaluating material and overall design choices, (2) simulating our prototypes as well as testing and presenting the results of the use of electric stimuli in multiple configurations of EarBloom's structure, and (3) assessing future works and applications to enable optimal functionality and protection.

Background

Current Commercial Hearing Protection Devices

The most commonly available and used commercial hearing protection devices (HPDs) are pre-molded ear plugs, foam ear plugs, and noise muffs (Wallace; Samelli). Pre-molded earplugs come in standard sizes and are reusable and relatively inexpensive. However, they must fit properly for them to work effectively, which is often a challenge. Foam ear plugs expand to conform within the ear canal and are typically only used one time (Samelli). Earmuffs cover the entire outer ear, which can be designed to fit most people. However, they are not appealing to use in hot climates and for long periods of time due to the heaviness of the product (NIOSH). Preferred sound attenuation levels and frequency of use of the HPD can influence one's preference among these commercial products (Arezes, P M and Miguel, A S). Commercial HPDs, especially earmuffs, create distorted attenuation of lower sound frequencies. This makes it difficult to conduct a conversation or hear the true sound quality of music while wearing the device. Additionally, many HPDs may not be comfortable for those with smaller ear canal diameters such as some women and children (Davis). High-fidelity hearing protection devices use small chambers within the device to allow high frequencies to resonate into the ear. This technology provides equal, non-distorted attenuation (Killion). However, they can be uncomfortable when worn for long periods of time. Our design focuses on the outer ear to avoid discomfort and misfitting of the device as well as a chamber design to address high-fidelity needs.

Sound Absorption

As audio digitization increased the importance of audio playback, studio and music makers explored new ways to preserve the quality of live audio in small studio rooms. For example, commercial sound manipulation panels alter sounds in different ways. Insulation in studio walls and corners are made out of fiberglass wool to trap low frequency sounds. Higher frequency sounds are absorbed by panels attached externally to the wall that are made of acoustic foam. This is done to prevent the incoming reflections in the sound, resulting in less echo and unnatural variations in the room's frequency response (Wertel). Reducing the reflections of sound waves across the room allows audio quality to be preserved for the listener.

In addition to studio panels, sound manipulating devices such as ear plugs were developed to find different ways to preserve sound quality. Particularly, sound absorption relies on both the inner-ear material characteristics and the design in order to properly absorb certain frequencies of sound to produce a desired result. New earplugs rely on additional resonating systems alongside sound absorbing material to account for the non-uniform attenuation of sound. Awareness regarding hearing protection has sparked an interest in the field of high-fidelity.

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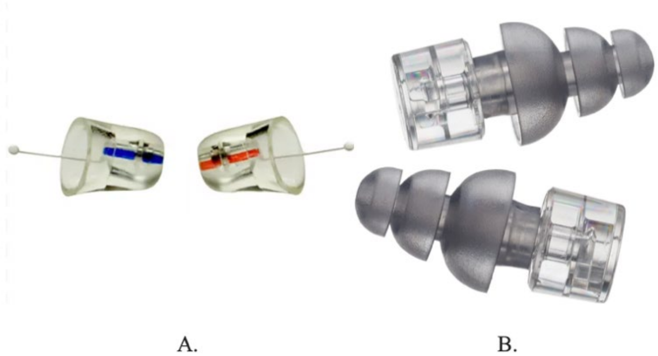


Figure 1. Image of Earasers High-Fidelity Ear Plugs (A) and Etymotic Research ER20XS High-Fidelity Ear Plugs (B).

Development in High-Fidelity Ear Plug Technology

High-fidelity ear plugs offer a new approach to the lack of musical applications for current hearing protection. Specifically designed for musicians and audio technicians, high-fidelity hearing protection preserves the quality of the sound while attenuating it at a safe level. Particularly in frequency response, quality, and timbre, high-fidelity ear plugs allow users to listen accurately to attenuated sound for critical monitoring or musical enjoyment.

Patricia A. Johnson, a doctor in audiology, described in her article "The High Notes of Musicians Earplugs" the need and mechanism for musicians to use different systems of high-fidelity hearing protection in order to prevent music-induced hearing disorders. High-fidelity hearing protection resembles normal ear plugs by creating an in-ear seal inside the ear canal. The goal of these quality-preserving ear plugs is to add back the higher frequency sounds that are muffled by material absorption. As such, many ear plugs utilize small chambers or antennas to add back the resonant peak that is lost in sound absorption. A common design includes chambers external to the ear canal which vibrate to increase the frequency at a certain frequency band, artificially increasing the resonant peak. A higher resonant peak will in turn boost the perceived higher frequencies. Another design includes antennas made out of thin filaments that vibrate at high frequencies. The incoming vibrations are sent back into the ear to regain the high frequency loss. The resulting sound of both systems is a quieter version of the audio perceived by the naked ear without altering the frequency distributions. The passive mechanisms in high-fidelity ear plugs allow them to be worn for long periods of time and allows for conversations to be heard while still protecting the user (Hickey).

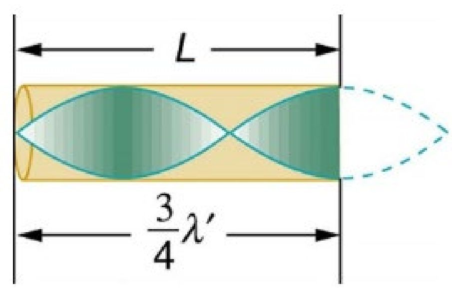


Figure 2. Model of resonance in small chamber.

Design Mechanics

Material Choice

Reticulated polyurethane foam—a type of porous foam—provides a lighter solution to dense absorption foam, therefore making it ideal for our device. This foam has pre-existing wide applications, indicating its ability to be mass produced and fabricated into the many modular areas of our hearing device. Its low cost allows it to be used in excess compared to high-costing metals that are also too heavy to be worn extensively on the ear. Finally, porous foam attenuates sound well, indicating that it has an inherent benefit as an acoustic metamaterial over commercially available ear plug materials (Gliqanic).

Common earplugs use dense foam, which causes ineffective and distorted sound absorption. Silicone earplugs and silica-based molds exist to create ear-shaped custom earplugs prescribed by audiologists. In addition, other earplug materials involve a combination of metals or natural fibers to further absorb sound waves. New developments have been made in acoustic metamaterials or materials altered specifically to increase sound absorbing capabilities. Notable inventions include metamaterial membranes that attenuate sound at a certain frequency and the creation of porous metamaterials. Porous metamaterials offer further absorption than normal foam, due to the intentional porous cell holes that trap the sound (Cao, et al.). In addition, porous metamaterials are cheap, offer more uniform attenuation, and can be made of natural materials such as an altered foam. The outer earpiece/shell of EarBloom onto which the porous foam petals attach will be made of silicone rubber due to its ability to conform to the user's ear shape and its high compatibility with human skin (Figure 3).

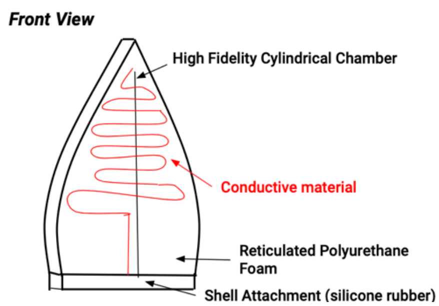


Figure 3. Front view of single petal with conductive material placement.

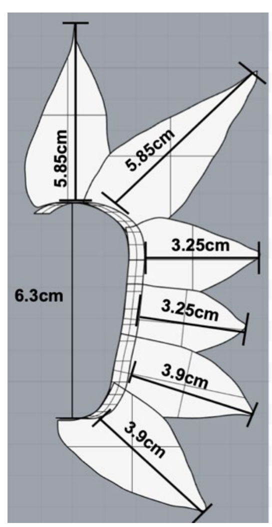


Figure 4. EarBloom device with dimensions.

Specifications

To ensure that the petals, when folded in, will effectively and completely cover the entrance to the inner ear canal and protect the wearer from loud noises, we researched the dimensions of the average ear (Brucker). We then based our petal lengths off those dimensions, considering each individual petal's distance from the entrance to the ear canal. After simulating the bending motion in 3D CAD software Rhino 7, we had to increase our original dimensions slightly to allow extra length for bending curvature. The ear hook is 6.3cm tall, and each petal is 1.4cm wide. The petals vary in size based on their location and distance from the inner ear canal: the top two petals are 5.85cm tall; the middle two, 3.25cm; and the bottom two, 3.9cm (Figure 4). The high-fidelity chamber within each petal is 2mm in diameter, and each petal is 5mm thick.

Sensors, Actuators, and Electrical Stimulus

When considering the actuation process for EarBloom, we propose an electric stimulus system that causes the petals to bend and the emergency airbag to inflate. This would require a small piezoelectric microelectromechanical systems (MEMS) microphone to detect sound and convert the acoustic pressure from the vibration of sound into electric currents (Littrell). This electricity would be supplied by a microbattery (Pikul et al.). If the sound increases, the amplitude of the analog feedback from the microphone increases as well. The electrical current then travels to the processing unit. This unit consists of two parts: peak detection and threshold circuitry. First, positive peak detectors identify large volume fluctuations (Geronimo et al.). Then, the thresholding circuitry compares the value of the detected peak to a given threshold of 85dB. Once it identifies a peak above 85 dB, a transistor on the circuit board opens to enable the electric current to travel through the main electric current flow on the earpiece hook and then branch onto the conductive material on each petal (Figure 4). The actuation system occurs through the presence of specific configurations of conductive material to direct the electrical current throughout each petal. Hence, when electricity flows along a petal, the bending motion will occur. We discuss these configurations further in the "Digital Design and Simulation of Petals" section of this paper. The petals will return back to their upright, uncurved positions when they are no longer receiving an electrical current (Wang). When no peaks of sound are detected, they will be in their normal, uncurled state, because they will not be receiving any electricity to put it in its active, bent shape. A second processing unit is on the circuit board to detect peaks above 110 db. Similar to what is described above, an electric current flow towards the emergency airbag when a peak above 110dB is detected. Again, we discuss this further in the section titled "Emergency Airbag Design and System." The control system block diagram in Figure 5 visually illustrates this process.

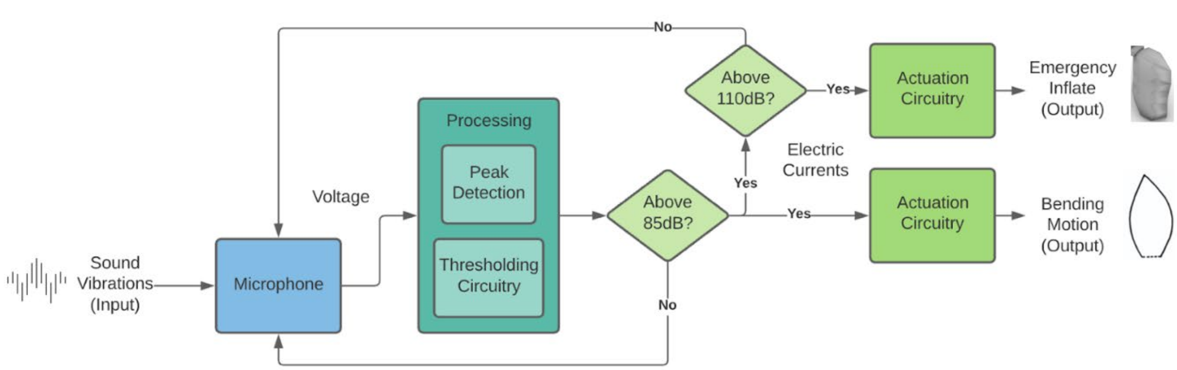


Figure 5. EarBloom Control System Block Diagram.

Design Morphology

Biomimicry Mechanics Design

EarBloom's actuation is inspired by the morphology of the blooming and closing petals of a lily flower. Lily flower petals use edge actuation while blooming, rather than surface actuation (Liang). This edge growth allows the petals to curl and morph into a more open shape beyond the general surface growth and rotation of the blooming petals. Similarly, the individual petal-like structures on our design curl inward when responding to a loud noise and outward when opening back up. This movement allows for minimal bulk rotation of the entire petal as well as a more natural morphology. Through edge actuation, the petals can more closely conform to the wearer's ear by curling towards the inner ear, thus providing maximum protection. Additionally, this feature adds to the aesthetic appeal of the device, as it more closely mimics the natural beauty of a lily flower. To further improve the aesthetic of our device, we modeled the surface pattern of the petals after the design of the eyespot on a peacock's train feather. Also, the inner high-fidelity chamber in our petals resembles the inner tube of the peacock feather.

Digital Design and Simulation

Our design process began with hand-sketches. We first sketched a scale design of EarBloom with the correct dimensions on paper. Next, we used Rhino 7 and parametric design plug-in Grasshopper to further design and test the device. The shape and size of the 3D model of EarBloom were modeled after our hand sketch. For the actuation, our initial design simply rotated each petal inwards about its base to cover the ear. The individual petals themselves remained rigid. While the end positions of the petals appeared promising, this design had its limitations. Actuation would most likely require either a motor to rotate the petals, which take significant power and requires heavy hardware components, or a more complex hinge bending actuation with a specific material. The latter would be difficult to fabricate. Additionally, this design did not look as natural as a real blooming flower. Due to these limitations, we experimented with bending the petals themselves to cover the ear. Table 1 shows the different bend arcs and starting points (indicated in each image as a small "x" at one end of the arc) we tested, and the resulting bend shapes produced. The red petal is the petal in its standard, unbent form and the blue petal is the produced result along that bend arc. We used Rhino 7 and Grasshopper to parametrically change the bending actuation of a petal for several different configurations. The starting points correspond to locations for where we would place the least conductive material for the electrical stimulus actuation due to them acting as anchor points. Figure 6 shows the equation used in the Grasshopper code to make the petals bend in response to a given decibel level. Testing and simulating different designs digitally allowed us to evaluate each configuration and make a well-informed decision about the stimulus and actuation process. We address our conclusions on this experiment in the results section of this paper.

Table 1. Possible configurations of starting points resulting in different bending shapes.

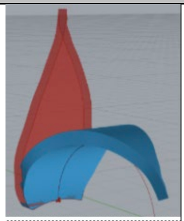
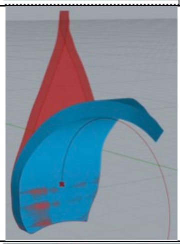
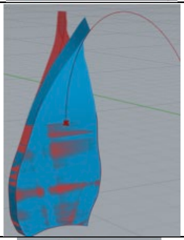
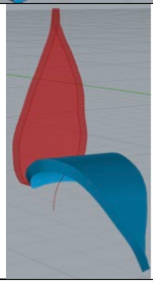
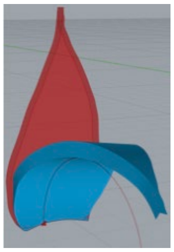
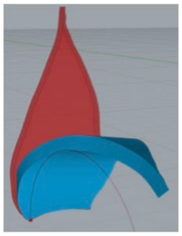
Bend Arc Starting Points	Resulting Bend Shapes
Base Center	
Slightly Above Base Center	
Middle Center	
Below Center	
Mid-left Base	
Left Corner	

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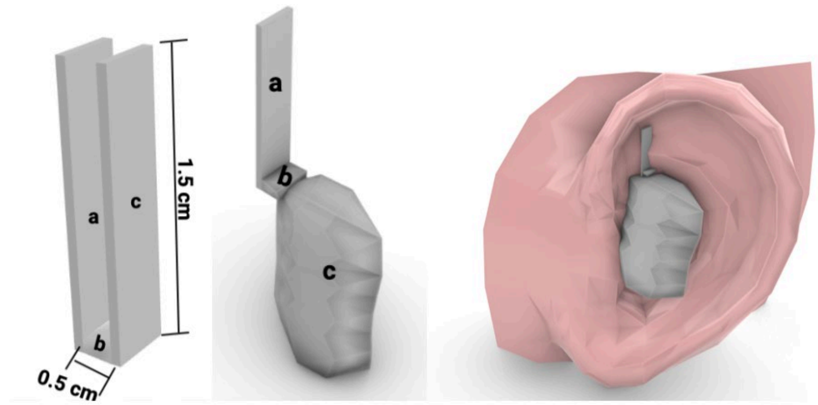
Figure 6. Key component of Grasshopper code for bending all petals in response to dB level.



A. B. C.

Figure 7. Rendered Rhino 7 Model of Emergency Airbag during “safe” sounds, which is less than 110 dB (A) and during dangerously loud volumes of at least 110 dB in its inflated form individually (B) and inflated within the human ear (C).

Emergency Airbag Design and System

We designed an emergency airbag system to prevent hearing damage at extremely loud, sudden volumes of 110 dB and greater (“What Noises Cause Hearing Loss?”). The model in Figure 7A represents the structure’s form during relatively safe volumes. However, when the device detects a volume greater than 110 dB, the middle piece (b) will begin to inflate, causing the collapsible anterior portion to rotate downwards as it inflates as well. The transformation of the inflated structure (c) downwards, as modelled in Figure 7B, is a result of the inflation and pressure of the middle piece. The rectangular left side (a) is directly attached to the rest of the EarBloom device. The inflated portion will conform to and protect the center of the ear (Figure 7C), including the entrance to the ear canal and ear concha to prevent hearing damage (Banglmaier). Figure 8 shows an overview of the Grasshopper code used to simulate this actuation. The inflation process relies on a chemical reaction that produces nitrogen gas immediately through the ignition of sodium azide (Madhu, S., and Kumar, Arun). Once the decibel input reaches above 110 dB, Earbloom’s microcontroller circuit will send an electrical current to the emergency airbag’s middle and collapsible portions to ignite the sodium azide within these areas. Sodium azide immediately reacts, forming nitrogen gas, which causes the airbag to inflate within the concha of the ear. The material used for the emergency airbag portions b and c will be nylon, for its strength and flexibility, which is also used commercially for airbags in vehicles (Madhu, S., and Arun Kumar). The material used for the stationary portion (a) will be silicone rubber to remain continuous with the hook earpiece part of the EarBloom device to which this portion attaches.

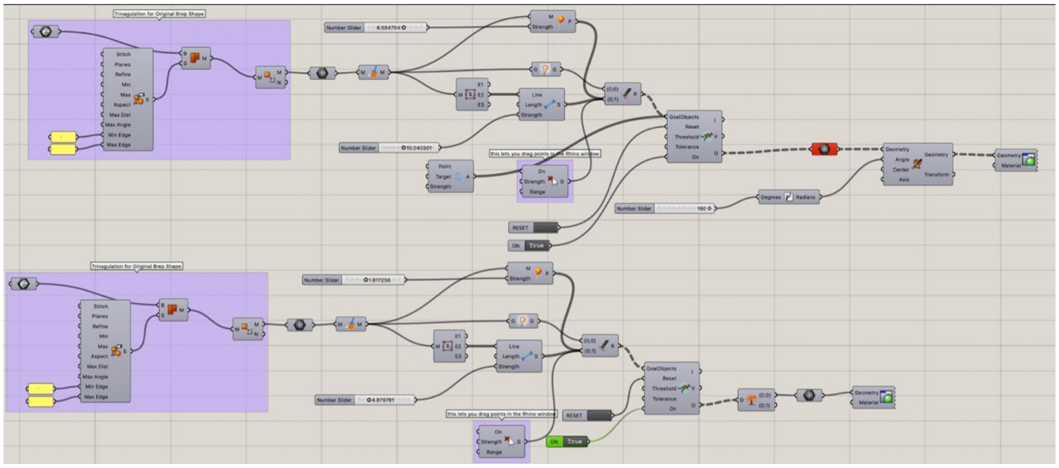


Figure 8. Grasshopper code for emergency inflatable mechanism.

Simulations of Varying Petal Thicknesses

To determine the optimal thickness of the petals for EarBloom, we conducted several static stress simulations on Fusion 360—a physics simulation platform—for each increment of thickness we were considering (Table 2). We tested the moment of inertia, which represents the amount of stress along the object depending on the direction the object would move in. We tested with a pressure of 10 Newtons for each test. The red regions represent areas with high stress, meaning they would be more likely to yield under tension. For the bending motion of our device, a dimension with a low stress would allow more control for actuation to occur continuously and would enable sturdier, more resistant petal structure when the petal is not in motion. The 3 mm and 7mm thickness both had areas of high stress, as depicted in the yellow, red, and orange areas towards the bottom of the petal in Table 2. Those thicknesses are therefore not ideal in situations where significant curvature occurs, such as in our device. Hence, the 5mm thickness proved to be the optimal dimension according to the static stress simulation. The 5 mm test revealed very low stress overall, meaning it would pose the greatest strength against any external tensile pressures from motion.

Results and Analysis

Bending Actuation

The results from our digital simulations of the bending actuation allow us to determine the optimal location for the conductive material relative to each petal. What is referred to as the “starting point” represents the location of the least amount of conductive material on the petal, acting as an anchor point. The simulation revealed that placing the starting point high above the base of the petal limits the petal’s ability to bend far enough to cover the ear; therefore, this is not the ideal configuration. However, having smaller amounts further up the petal would be useful in bending the petals only slightly in situations with mildly loud sounds. Placing the starting point at the center of the base on the front face or below the base produced the most ideal bending shapes. The petal was able to bend downwards, protecting the ear and mimicking the movement of a blooming and closing flower. Placing the starting point either partially off-center or at the corner rendered similar results.

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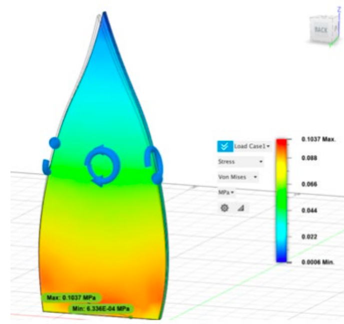
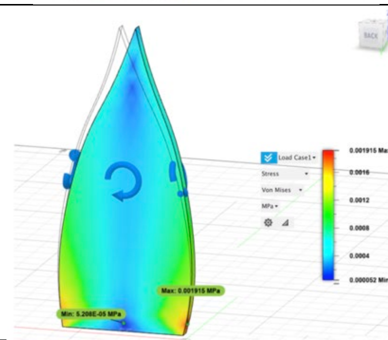
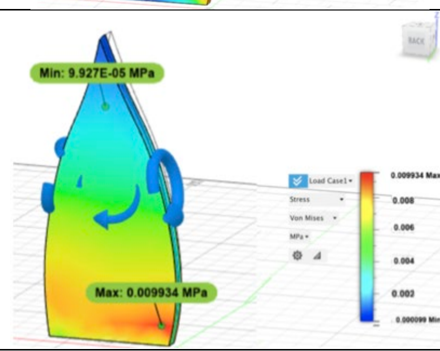
Table 2. Static stress simulations of Silicone Rubber Material single petals on Fusion 360 for incremental thickness levels (3mm, 5 mm, and 7 mm) to test for strength with 10 Newtons of pressure applied against the petal.

EarBloom Thickness per Petal	Static Stress Simulation Results in Autodesk Fusion 360
3 mm	
5 mm	
7 mm	

Both would be useful for bending at an angle, as in if the final target location is in the vertical direction as well as to one side. Figure 9 demonstrates the bending of the petals from the center base for the straight full bends, from off-center base for the angled full bends and from points above the base for slight bends in response to increasing dB levels. Figure 10A shows the full design open, and Figure 10B shows the full design in the closed position.

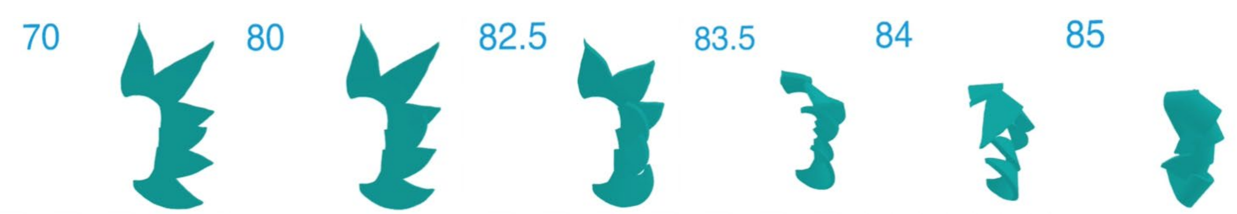


Figure 9. Image sequence of bending motion at increasing dB levels (70, 80, 82.5 83.5 84, 85 dB).

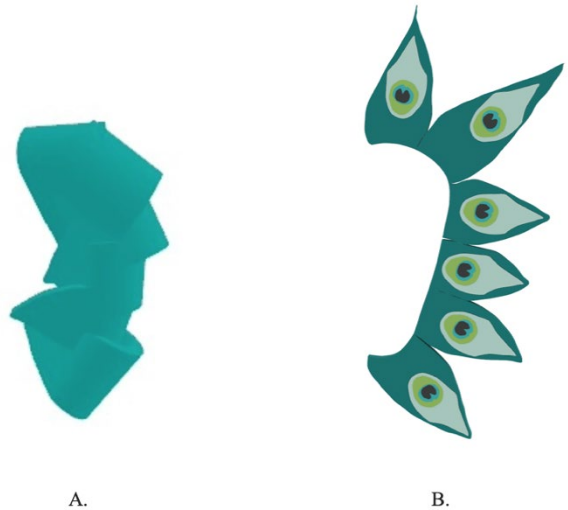


Figure 10. 3D Rendering of Final EarBloom design in closed position (A) and open position (B).

Final Results

Based on our simulation results and 3D animated model, EarBloom presents a successful solution to our original research question of integrating hearing protection and fashion in the context of morphological computation and wearable technology. EarBloom's soft robotic structure and automatic actuation provides the wearer with hearing protection from noise pollution while also incorporating aesthetic appeal. Figure 9 shows the device at several points during the bending actuation at increasing dB levels, displayed as the number in the top left corner of each image. The device is able to rest comfortably on top of the ear while not in use, as in Figure 11A and then bend to conform to the ear when providing protection from loud noises, shown in Figure 11B. The use of electrical stimulus and conductive material to induce actuation proved to be effective and feasible. In addition, our emergency inflatable airbag successfully fills the inner ear concha to block out extremely loud noises when necessary. We also improved on current hearing protection devices by maintaining comfort while also creating even sound attenuation through the use of high-fidelity chambers (Killion).

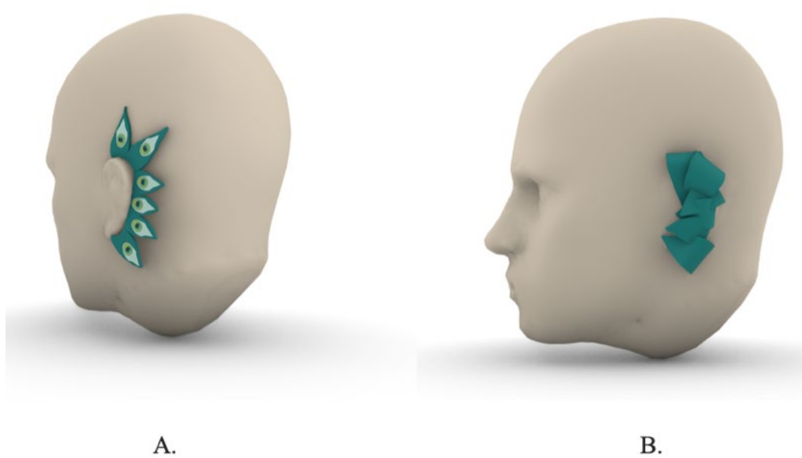


Figure 11. Final EarBloom Design Open (A) and Closed (B) on Human Head.

Discussion

We have presented EarBloom and have explained how it provides hearing protection while also integrating fashion technology, soft robotics, and biomimicry. We discussed that our design is inspired by both the natural blooming and closing of a lily flower and the physical design of the peacock feather. We presented the limitations of current hearing protection devices and how EarBloom overcomes those limitations. EarBloom utilizes an electrical stimulus to produce bending actuation and an emergency inflatable component for extremely high volumes. Our team modeled, simulated, and tested EarBloom in 3D modeling software Rhino 7, parametric design plug-in Grasshopper, and physics simulator Fusion 360. Lastly, we addressed acoustic materials and high-fidelity technology in our design.

One limitation of our current design is the single-use inflatable air bag. In future work we hope to address this limitation by designing a reusable element for emergency situations. Another area we would like to address further is the limitations with the device's inability to create a completely airtight seal around the ear canal in order to further optimize sound protection. Future research could address this limitation by finding a solution to the health and safety risks of having a moving part of a device inserted far into the inner ear canal. Additionally, we hope to manufacture and test a physical prototype of our design to go beyond the virtual setting in the future. We would also like to increase the degrees of freedom of the petals on our device and allow it to respond specifically to directional stimulus. Finally, our vision for the future of this research could involve the device responding to additional human senses, as this would be an interesting area to explore.

Conclusion

EarBloom can combat noise pollution by providing ear protection in parallel with a visual commentary on loud, everyday environments. It also offers users a fashionable solution to hearing damage and loss, providing people with a stronger incentive to wear hearing protection. EarBloom highlights the interaction between the sensory input of sound from the environment and a morphological response of a wearable soft robot to serve in both medical and aesthetic applications.

Acknowledgments

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