MouthIO: Fabricating Customizable Oral User Interfaces with Integrated Sensing and Actuation

Yijing Jiang
Aarhus University
Aarhus, Denmark
y.jiang@cs.au.dk

Julia Kleinau
Aarhus University
Aarhus, Denmark
julia.kleinau@cs.au.dk

Till Max Eckroth
Aarhus University
Aarhus, Denmark
tillmax@eckroth.de

Eve Hoggan
Aarhus University
Aarhus, Denmark
eve.hoggan@cs.au.dk

Stefanie Mueller
MIT CSAIL
Cambridge, USA
stefanie.mueller@mit.edu

Michael Wessely
Aarhus University
Aarhus, Denmark
michael.wessely@cs.au.dk

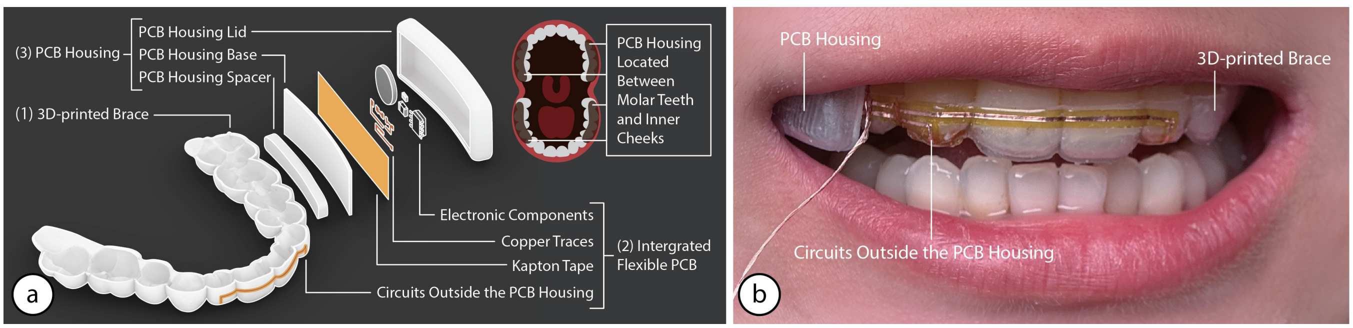

Figure 1: (a) MouthIO schematic. The oral interface consists of three components: (1) the 3D-printed brace that gets attached to the teeth, (2) the integrated flexible PCB with circuits, battery, microcontroller, and sensors, and (3) the PCB housing to water-proof encapsulate the electronics and make it bite-save. (b) Wearing a MouthIO interface integrating two capacitive touchpads that enable the detection of tongue tapping, serving as an assistive tool for users with motor impairment.

ABSTRACT

This paper introduces *MouthIO*, the first customizable and open-source intraoral user interface that can be equipped with various sensors and output components. *MouthIO* consists of an SLA-printed brace that houses a flexible PCB within a bite-proof enclosure positioned between the molar teeth and inner cheeks. Our *MouthIO* design and fabrication technique enables makers to customize the oral user interfaces in both form and function at low cost. All parts in contact with the oral cavity are made of bio-compatible materials to ensure safety, while the design takes into account both comfort and portability. We demonstrate *MouthIO* through three application examples ranging from beverage consumption monitoring, health monitoring, to assistive technology. Results from our full-day user study indicate high wearability and social acceptance levels, while our technical evaluation demonstrates the device's ability to withstand adult bite forces.

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CCS CONCEPTS

• **Human-centered computing → Interaction devices**; **Ubiquitous and mobile computing**.

KEYWORDS

Oral Interface, Wearable Computing, Fabrication, Flexible Circuits

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1 INTRODUCTION

Wearable electronics are widely used for health monitoring and to sense user interaction as they are readily available to capture input and often have continuous access to the user's bio-signals, such as the user's heart rate. However, most wearable devices are worn on the skin or integrated into textiles, while intraoral wearable technology that is worn inside the mouth is still rare.

Recent research has demonstrated that oral interfaces can provide a variety of discreet hands-free and eyes-free interactions and help improve the efficiency of multitasking [19, 38]. In addition, they can serve as assistive technologies to help people with physical disabilities regain basic interaction capabilities via tongue-controlled wheelchairs and computers [26, 54]. Oral interfaces also provide significant advantages in bio-monitoring. For example, saliva can be tested through biochemical ligatures on braces to detect metabolism changes [56]. Specific diseases such as diabetes [8], xerostomia [53] and bruxism [14, 33] can be reliably detected by sensors located in the user's mouth.

However, current devices used for these applications require complex electronic manufacturing processes and advanced dental equipment that are often unavailable outside of specialized labs. In addition, all of the devices are specifically made for a single purpose and do not offer customization of the brace's geometry and embedded electronics to support different application areas. To address this issue, we investigate how to design and fabricate oral user interface that are customizable for various applications.

We present MouthIO, a design and fabrication method for customizing fully self-contained wearable devices that integrate microcontrollers and batteries as the base components, and can house a multitude of sensing and actuation components. We also present a novel open-bite design for the MouthIO brace, which we developed because typical braces fully enclose the teeth of the user, and cause a more uncomfortable biting and speaking experience. In contrast, our open-bite design leaves the tips of the teeth uncovered. Our user study indicates that the open-bite design is preferred by users because of its increased comfort and, due to its reduced visibility, leads to higher social acceptance. We demonstrate the full design and fabrication process, from obtaining a 3D model of the user's teeth to printing the brace with bio-compatible resin and integrating electronic components, which enables researchers, dental technicians, and experienced makers to fabricate MouthIO braces. Our technical evaluation shows that the MouthIO PCB housing can withstand adult bite forces (662N-2,173N) without suffering any damage to the internal electronics and batteries. We demonstrate the utility of MouthIO with three application examples in beverage monitoring, health monitoring, and assistive technology.

In summary, the contributions of this paper are:

- a design and fabrication technique for oral interfaces that are fully self-contained, and comfortable to wear, while supporting a multitude of input and output components;
- a technical evaluation on the mechanical durability of MouthIO;
- a user study on the wearability and social acceptance of MouthIO braces;
- three application scenarios on health monitoring, beverage monitoring, and assistive technology.

2 RELATED WORK

Our work is related to interactive oral technologies, DIY wearable electronics and prototyping toolkits, as well as flexible circuits and sensors.

2.1 Interactive Oral Technologies and Devices

Research and commercial products on oral interface technology cover applications in health monitoring, hands-free interaction, and accessibility. For instance, the Bruxism Monitor [14] employs piezoresistive sensors to measure the frequency and intensity of teeth-grinding events. Researchers also embedded a three-axis accelerometer into a mouth guard that tracks accumulated head impact forces during contact sports [11]. Other research focused on intraoral biosensors that are used as indicators when interacting with saliva. For example, BraceIO [56] used biochemical materials on dental braces to identify changes in saliva composition by altering color, and Mannoor et al. [41] presented a graphene-based sensor that has been tattooed onto tooth enamel for detecting respiration and bacteria in saliva. Furthermore, Arakawa et al. [8] integrated a glucose sensor inside a mouth guard to monitor salivary glucose. Jayoung et al. [32] proposed integrating a biosensor into a mouthguard that can sense salivary uric acid. However, these devices require advanced manufacturing processes and laboratory equipment (e.g., parallel plate sputtering to form electrodes or application of enzyme membranes), making them difficult to replicate outside specific laboratories.

Other oral technologies enable hands-free interaction by using sensors to detect motion. For example, Sahni et al. [48] placed a magnet on the user's tongue which is tracked using a magnetometer in Google glasses to detect tongue and jaw movements during silent speech. In contrast, ByteIt [57] positioned an IMU sensor outside of the user's mouth near the ears to detect clicking vibrations when biting on teeth at different locations in the mouth. Yet all these devices require external sensing outside of the user's mouth, which is not discreet. One exception is ChewIt [19], which allows users to perform various hands-free input operations with an IMU sensor embedded in a 3D-printed housing that the user can put in their mouth and interact with using their tongue and teeth. However, users have to consciously hold it between their teeth or interact with their tongue which might hinder speech and make it unfavorable for long-term use.

Intraoral tongue control technologies can also significantly enhance accessibility. Andreasen Struijk et al. [7] developed a tongue-based robotic control method incorporating a multi-sensor inductive tongue interface, allowing individuals with tetraplegia to control assistive robotic arms. Tongue Drive System [31] and Inductive Tongue Control System [54] utilize magneto-inductive sensors on the user's tongue to track tongue movements providing computer access and environmental control for severely disabled individuals. However, these technologies require a permanent magnet secured on the tongue by implantation, piercing, or tissue adhesives and do not support other oral sensing modalities than tongue tracking.

The focus of commercial products so far has been on developing oral devices to provide individuals with varying degrees of physical disabilities with alternative ways of interacting with computers and devices. For example, both Jouse [3] and IntegraMouse [2] present a joystick-operated solution for the screen cursor control, whereas the LipStick [4] offers a force stick as a mouth-operated computer mouse. However, they are not mobile devices, so users are restricted to using them in stationary positions, limiting mobility. Recently, Augmental introduced the MouthPad [1], a pressure-sensitive touchpad in the palatal area of the mouth that can be used to interact with data using the tongue. Although similar in fabrication, its functionality cannot be customized by makers, while MouthIO is an interaction prototyping platform that supports various sensors and output components.

These studies and products showcase the diversity of oral interface technology, offering various modalities for user interaction including tongue tracking and bite detection on teeth. However, all of these systems feature a dedicated system often supporting only one specific sensing modality. In contrast, MouthIO supports prototyping with custom PCBs that can house a variety of different sensors (e.g., touch, accelerometers, temperature sensors) and actuators (e.g., vibration motors, LEDs) and can be customized in their shape to support diverse teeth geometries and requirements.

2.2 DIY Wearable Electronics and Prototyping Toolkits

Rapid advances in material science, electrical engineering, and computing technologies have made DIY wearable electronics a research field of growing interest. Several studies have explored conductive materials, such as gold leaf [29], conductive yarn [65], and conductive gels [28] as well as fabrication techniques with commodity machines, such as inkjet-printers [45], 3D printers [16], screen printing [62], silicone casting [43], and weaving machines [24, 64] to achieve rapid do-it-yourself on-body prototyping of interactive wearables and devices.

At the same time, HCI researchers proposed toolkits to support rapid prototyping for personal fabrication of wearables and physical user interfaces. For instance, ThermoFit [59] is a fabrication pipeline that enables integrating electronics on auxetic metamaterials for smart orthotics on the body. FlexBoard [34] enables prototyping on curved and deformable substrates like textiles and human skin with a flexible breadboard. Instead of prototyping directly on the physical object via breadboards, MorphSensor [66] proposes a digital design tool to distribute the electrical components of sensor modules on the 3D surface of objects before they are printed. SkinKit [36] is a construction toolkit for on-skin interfaces with reusable flexible printed circuit board modules.

Although various research has been looking into fabricating on-skin and on-body electronics, the potential of fabricating electronics in the oral cavity is currently largely unexplored. Unlike the skin, the oral cavity is a humid environment with complex and compact geometries, which makes it challenging to place circuits and electronic components in it. Instead of placing electrodes inside the mouth, LipIO [27] distributes touch sensors and electro-tactile electrodes near the mouth on the user's lips that act as input and output elements. Similarly, TactTongue [42] also renders electro-tactile stimulation but locates it on the tongue, and investigates the integration of oral electronics. It demonstrates the possibility of customizing the interplay between tactile perception and flavors on the tongue. However, its design scope focuses on electro-tactile stimulation of the tongue and requires a flexible PCB to connect to the inside and outside of the mouth. In contrast, MouthIO presents the first multi-purpose prototyping platform for wearable intraoral interfaces.

2.3 Prototyping Flexible Circuits and Sensors

Prototyping physical user interfaces in the oral cavity requires flexible and soft electronics that can conform to complex geometries like the user's teeth or adhere to flexible substrates like the tongue. Previous research has looked into methods like thermoforming sheet materials with conductive traces to prototype 3D shapes [22, 23], translating flat conductive patterns onto 3D surfaces by hydroprinting [20], directly constructing 3D patterns by 3D-printing conductive filaments [6, 10, 49] or spraying conductive paints [21, 61].

Although these methods effectively produce conformal circuits, the conductivity of the traces created by conductive inks and filaments is relatively low. This can be a challenge when creating miniature circuits within the confined space of the oral cavity since the traces have to be very thin which leads to a high resistance. Instead, circuits made of copper offer higher conductivity and, thus, can also be used to prototype flexible miniature circuits. To achieve high-resolution circuits, researchers and makers have used off-the-shelf machinery like laser cutters [37, 63] and vinyl cutters [50] to process the copper foil. We build upon this research and integrate vinyl-cut flexible copper circuits and electronic components into our MouthIO braces that conform to the teeth geometry and withstand the moist intraoral environment.

3 MOUTHIO

Prototyping oral interfaces with MouthIO enables makers and researchers to embed interactivity in a near-invisible area of the body while being suitable for long-term usage and not hindering the user in many daily activities. To create such interfaces, we identified five key challenges.

3.1 Design Goals

Comfortable Wear. Using MouthIO should be comfortable and unobtrusive to wear during daily activities including talking, drinking, and sleeping. Thus, our design constraints include minimizing the integrated electronics and locating them in a comfortable location inside the mouth. The palatal vault space, i.e. the area at the center of the upper jaw between the molar teeth, is an area commonly used for the placement of intraoral devices. However, this location hinders the correct tongue posture and movement required for clear speech [25, 47]. Thus, MouthIO has the housing of electronics located in the space between molar teeth and inner cheeks, which leaves the palatal vault space free for the tongue when talking and offers enough space for a full circuit including a battery, microcontroller, and sensors. The shape of the device should avoid corners and sharp edges, as they are uncomfortable and may even cut the soft mouth tissue. Thus, we designed the PCB housing to have round edges to improve comfort.

Safety. All materials that come into direct contact with the mouth need to be non-toxic and food-safe. We use Formlabs Dental LT Clear Resin[1] as the encapsulation material. It is a bio-compatible material with FDA registration and MDR certification intended for long-term use in the mouth. The PCB housing is SLA-printed together with the brace, safeguarding the internal electronic components and circuits from being bitten or exposed to the user's

[1] https://formlabs.com/eu/store/dental-lt-clear-v2-resin/

saliva. We also place water contact indicators[2] on each PCB to guarantee a water-proof PCB housing. Our technical evaluation demonstrates that the housing can withstand at least 662N pressure without getting damaged, which is below the average bite force of adults (285N [55]).

Mobility. Oral user interfaces have to be mobile since they should be usable also during other daily activities. This requires a mobile power supply and some applications also require a wireless communication module (e.g., Bluetooth). The PCB housing of MouthIO braces is large enough to house one or multiple coin cells with 12mm diameter (CR1220). It is also possible to integrate modules for wireless charging (e.g., WT151512-22F2-ID) or small Bluetooth antennas (e.g., SLDA31-2R400G-S1TF).

Wide Range of Functionality. Current oral user interfaces utilize specific sensors for specific application scenarios (e.g. electro-tactile stimulation on the tongue [42]). To support makers in prototyping novel types of oral interfaces, MouthIO supports custom PCB designs that enable makers to have design freedom for the integration of sensors and output components for custom oral user interfaces. Our fabrication technique supports iterative prototyping of well-known oral devices (such as assistive technologies for bruxism [14]) and, in addition to previous techniques, supports customization and iterative prototyping for a broad set of novel applications and form factors.

Accessible Fabrication. All components of MouthIO are fabricated with commercially available materials (e.g., dental impression spoons, alginate paste) and machines that are available in many Fablabs (e.g., resin printers, vinyl cutters). The material cost for one MouthIO print is around $4 and 3D printing takes only 2h. Our PCBs are fabricated with inexpensive Kapton tape and copper foil or they can be purchased at low cost from a PCB manufacturer which is below $10 for many electrical components. Making a teeth model requires plaster and alginate paste at a total cost of less than $1 per model. Finally, makers can scan the physical model with a mobile phone app (e.g., with Polycam, $100 for the pro version).

3.2 Implementation

MouthIO consists of three main components: (1) the 3D-printed brace, (2) a PCB housing that is attached to the brace, and (3) a flexible, integrated PCB (Figure 1a). In the following, we will describe each of these components.

3D-printed Brace. The brace gets attached to the teeth and holds the electronics and the PCB housing. It is 3D printed with biocompatible dental resin and a wall thickness of 1mm to increase the comfort of wearing. The brace has to closely follow the topology of the user's teeth (1) on the inside fitting tightly to the teeth to not fall off, and (2) on the outside to ensure a natural bite from the opposing jaw. Depending on the application scenario, MouthIO can be printed both for the upper and the lower jaw. To improve the comfort of wearing MouthIO, we modify the brace in two ways: (1) we integrate a spacer between the brace and PCB housing to avoid pressure on the gum (Figure 1a), and (2) we propose a new brace design that leaves the tips of the teeth open. The latter is particularly useful to avoid lisping as the tongue can touch the front teeth (Figure 2). During the fabrication process, makers can choose whether the brace is an open or closed design according to their requirements. Our user study (section 7) identifies that most participants prefer our open-bite design over a closed brace.

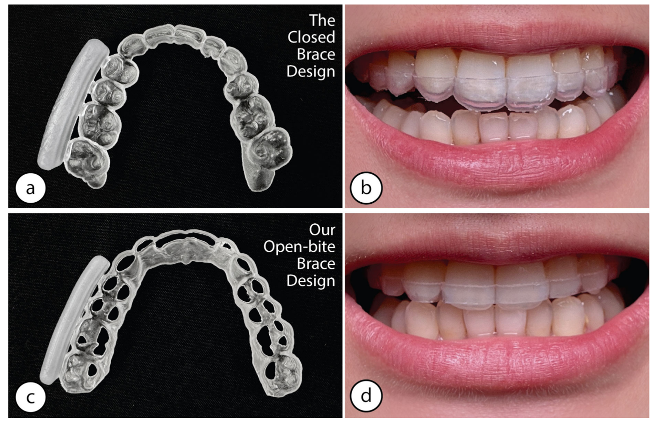

Figure 2: (a) The traditional closed brace design. (b) Wearing a closed brace. (c) The Open-bite brace design. (d) Wearing an Open-bite brace. The open-bite design leaves the tip of the front teeth open which reduces lisping.

PCB Housing. We encapsulate the PCB and all electronics including the battery in a 3D-printed bite-safe housing (Figure 1a). The housing is curved following the shape of the brace. To prevent accidental bites, the PCB housing is positioned away from the biting surface of the molar teeth, making it difficult for the opposing teeth to come into contact with it. To be able to insert the electronics, we print the PCB housing in two pieces: a bottom piece that holds the electronics and a lid. After inserting the electronics, we place the lid on top, seal it with the dental resin and cure it inside the Formlabs washing and curing station. To support iterative prototyping, makers can test the functionality in situ and modify their design with our MouthIO design plugin. When the design is final, makers can fill up the entire PCB housing with dental resin and cure it inside a curing station. This improves the stability and bite-resistance of the MouthIO interface for long-term use.

Integrated Flexible PCB. The flexible PCB holds the core electronics for a MouthIO interface including batteries, a microcontroller, and custom sensors. We propose two methods for creating the MouthIO PCB: (1) an in-house method using copper foil and a vinyl cutter for fast design iterations, and (2) a commercial flexible PCB for high trace resolution and reliability. The in-house method uses a vinyl cutter to cut copper traces out of a piece of copper foil. We choose copper tape as the main material because of its high conductivity and ease of cutting. Before cutting, we adhere the copper foil to a piece of Kapton tape to secure the copper traces. After fabricating the flexible PCB, we solder all electronic components

[2] https://www.3m.com/3M/en_US/p/c/electronics-components/electronics-films-tapes/water-contact-indicator-tapes/

on the PCB. This method is especially useful for fast design iteration and testing out various configurations of sensors and their placement. Once a final design has been found, makers can send their PCB design to a manufacturer who produces a higher quality PCB which optionally can have all electronics already soldered in place.

Electronics outside the PCB Housing. Some applications might require placing sensors or actuators outside of the PCB Housing. For example, placing touch-sensing pads on the brace can be useful for tongue-tapping interfaces for users with motor impairment (Figure 1b). To enable such user interfaces, the maker can extend the PCB outside of the PCB housing and place small components on the brace. This is intended only for small components like flat copper traces (e.g., for touch sensing) or small SMD components (e.g., a temperature sensor). To ensure the safety of these components, makers should apply three layers of dental resin on all exterior components and PCB traces and cure them in a washing and curing station.

4 DESIGN AND FABRICATION PROCESS

We next describe our design and fabrication process for making custom oral interfaces. In the following section, we will describe the fabrication of the brace, the electronics, and the PCB housing, and introduce our MouthIO design tool for generating 3D print files.

4.1 Target Audience

MouthIO can be fabricated with commercially available materials and machines. In addition, our design tool is a plugin for Blender, a widely used 3D editor. The material cost for one MouthIO print is around $4 plus the costs for the PCB which is for many electrical components below $10. Thus, our system is not only accessible to experts, dental technicians, and researchers, but also to experienced makers. However, some steps in our design tool require practice, e.g., the maker has to remove the gum parts of the digital mesh manually which might require practice and multiple attempts to get a comfortable and tight fit for the individual user. Thus, our system requires some practice for makers to master.

4.2 Generating 3D Model of Teeth

The MouthIO design tool requires a 3D model of the user's teeth to generate a comfortable brace. We discuss two methods to accomplish this, i.e. a professional 3D scanner that can scan teeth directly, and a DIY approach that requires casting a physical model of the teeth and subsequent scanning with a mobile phone app.

Professional Teeth Scanner. The first method requires specialized dental 3D scanners and software (Figure 3a), which are often available in professional dental clinics. For example, iTero[3] offers a hand-held scanning tool that users have to move around their mouth while it is scanning the teeth geometry. The software then outputs a textured geometry file that can be used for further processing. These scanners offer high accuracy but are more costly with the iTero scanner available from $20,000, making this option expensive and inaccessible due to its high cost.

[3]https://itero.com/

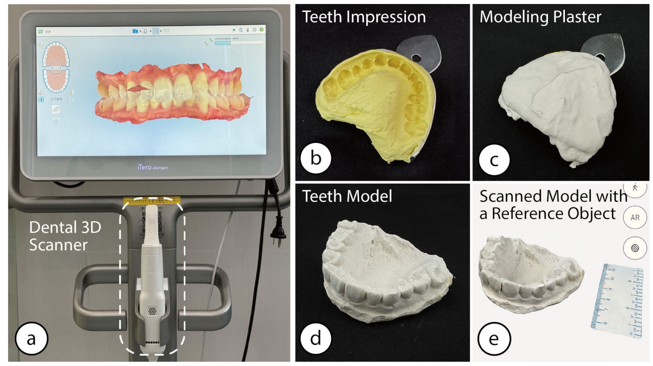

Figure 3: (a) A professional dental 3D scanner generating a 3D scan. Alternatively, makers can create a model by creating (b) an impression with alginate paste and a dental impression spoon, (c) filling the impression with modeling plaster, (d) removing the model from the mold, and (e) scan the model with a reference object in the Polycam app.

DIY Plaster Model. An alternative approach is to use dental impressions and plasters to create physical models of the teeth. First, makers fill a dental impression spoon[4] with a dental-grade alginate paste[5]. After mixing for 30s, the user then bites into the alginate paste for 90s to create an impression of the teeth (Figure 3b). Makers then fill the resulting impression with plaster[6] to produce a model of the user's teeth (Figure 3c). To remove any air bubbles, makers can add plaster in batches and shake the mold. The plaster should be cured at room temperature for at least 3 hours (Figure 3d). To obtain a digital model of the teeth, makers can scan the physical model with a mobile phone app (e.g. Polycam[7]) (Figure 3e). During scanning, makers can place a reference object (e.g. a coin) next to the mold to obtain a precisely scaled model. While this method may not offer the same level of accuracy as professional scanners, it provides a more affordable solution since all components can be purchased at low cost. Experienced makers can finish the whole process in 4 hours, including 3 hours of plaster curing time. We used this method for all application examples and the user study.

4.3 Model Processing with the MouthIO Design Tool

After obtaining a digital model of the user's teeth, makers process the model to create a 3D printable MouthIO brace. They can use native tools of Blender and our MouthIO plugin for Blender to prepare the model in 3 steps: (1) cleaning the model, (2) generating the PCB housing, and (3) integrating PCB designs.

[4]Tiiyee Stainless, Steel Dental Trays
[5]Wagner Silicones Alginat, https://www.zahntechnikshop.de/en/p/alginat-algistar-regular-set-3-4-min-colour-indicator-aroma-tropic-fruits-453-g
[6]Meyco Hobby Modelling Plaste, https://shop.meyco.eu/main/index.php?main_page=index
[7]Polycam, https://poly.cam/

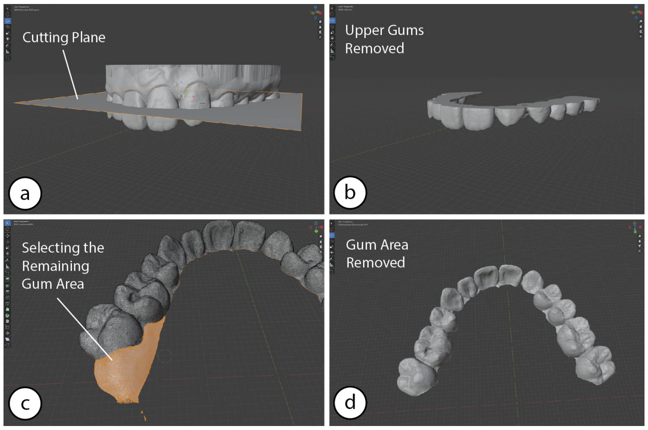

Figure 4: Preparing the MouthIO brace. (a) Users click in our Blender plugin on 'Create cutting plane' and (b) remove the upper gum area by dragging the plane to the desired height and clicking 'Cut Mouth Piece'. (c) Users remove the remaining parts of the gums by brushing over the particular areas using the 'Select Circle' tool of Blender and (d) deleting them by pressing 'x'.

Cleaning the 3D Model Geometry. 3D scans often come with some of the gums below the teeth still in the model. For comfortable wearing, we recommend removing all gums from the model. To simplify this process, we implemented a cutting tool that creates a plane above the teeth model (Figure 4a) that makers can drag down along the z-axis until most of the gums are above the plane. By clicking on 'Cut', the parts above this plane get removed from the model (Figure 4b). We recommend positioning the cutting plane slightly above the center of the upper teeth and checking if most of the gums around the molar teeth are above the cutting plane. In the open-bite design, makers can create a second cutting plane that gets placed slightly below the front teeth to cut open the tip of the teeth. All parts of the brace should not be thinner than 1mm to ensure mechanical stability. To remove the remaining parts of the gums, makers can use the 'Select Circle' Tool of Blender in 'Edit Mode' which allows them to select vertices by just brushing over them (Figure 4c), and deleting them (Figure 4d).

Generating the PCB Housing. Once the teeth model is cleaned up, makers can generate a PCB housing that gets attached to the teeth model. Makers start by selecting the size of the PCB housing, then they can select if the side walls of the PCB housing should be on the base or on the lid, and click on 'Create' (Figure 5a). Our plugin generates the PCB housing and automatically places it next to the first molar tooth by finding the vertex with the largest x-value (Figure 5b). The z-position of the PCB housing is derived from the smallest z-value of the entire model which we move up by 1.5mm to avoid any accidental bite on the housing due to overhang. The housing is also curved by 10° to more closely fit to the user's teeth. After generating the model, makers can adjust the housing's location to fine-tune it to the model. Next, we convert the teeth surface into a volume by clicking in our MouthIO tool on 'Create Volume' (Figure 5a). Makers can select the thickness of the brace by changing the value in the 'thickness' text field (std: 1mm). This also connects the brace to the spacer while the volume expands and merges into the spacer (Figure 5d).

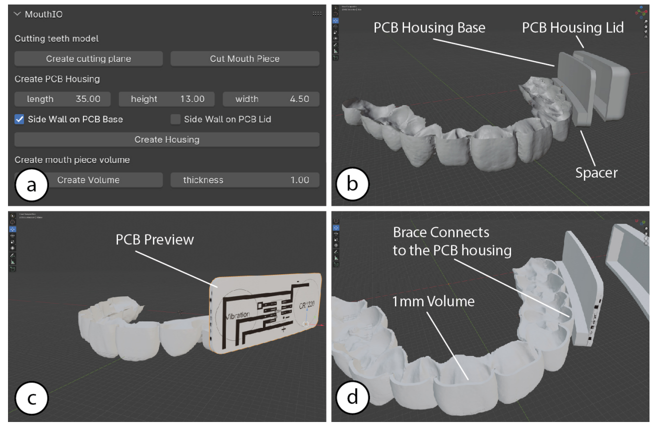

Figure 5: Adding the PCB housing to the MouthIO brace. (a) Users select the size of the PCB housing and click in our Blender plugin on 'Create Housing' which (b) gets automatically placed next to the molar teeth. (c) A PCB layout can be previewed as a texture to (d) ensure the right dimensions and location.

Integrating PCB designs. After deciding on the dimensions of the PCB housing, makers can custom design a PCB in dedicated design software (e.g., KiCAD) scaled to the size of the housing (Figure 7a). The PCB has to be 1mm smaller than the PCB housing on all sides to make space for the lid. To preview the PCB, makers load the PCB as a texture into Blender (Figure 5c). External traces and electric components outside of the housing have to be added in the PCB design software. To get their dimensions, we use Blender's measurement tool directly on the model. Makers can export the resulting meshes as a .stl file and load them in a slicing software for SLA printing.

4.4 Fabrication

After preparing the digital model, makers are ready to print the braces, fabricate the flexible PCB and assemble all components.

Printing and Post-Processing the Braces. We print all MouthIO braces with a Formlabs Form 2 resin printer[8] using the slicing software PreForm[9]. After printing, makers should post-process the braces by washing them with isopropyl alcohol (IPA) (e.g. using FormLabs Form Wash[10]) and curing them with the UV light (e.g. using FormLabs Form Cure[11]). This cures any uncured resin, ensuring food-safe and high-quality prints. Finally, makers can remove the support material by putting the braces in hot water and rubbing the support material off, or using a Dremel 8200 with a cutting wheel (Figure 6a). To remove residual bumps from the support,

[8]https://formlabs.com/eu/3d-printers/form-2/
[9]https://formlabs.com/eu/software/preform/
[10]https://formlabs.com/eu/store/post-processing/form-wash/
[11]https://formlabs.com/eu/store/post-processing/form-cure/

makers can polish the braces with a Dremel 8200 and a sanding bit to smooth the surface (Figure 6b) and achieve comfortable wear. We also recommend polishing sharp edges of the open-bite design near the tip of the teeth. Finally, makers can put the brace on the teeth model to check if it fits (Figure 6c). If the brace doesn't fit, makers may need to rescale and reprint it.

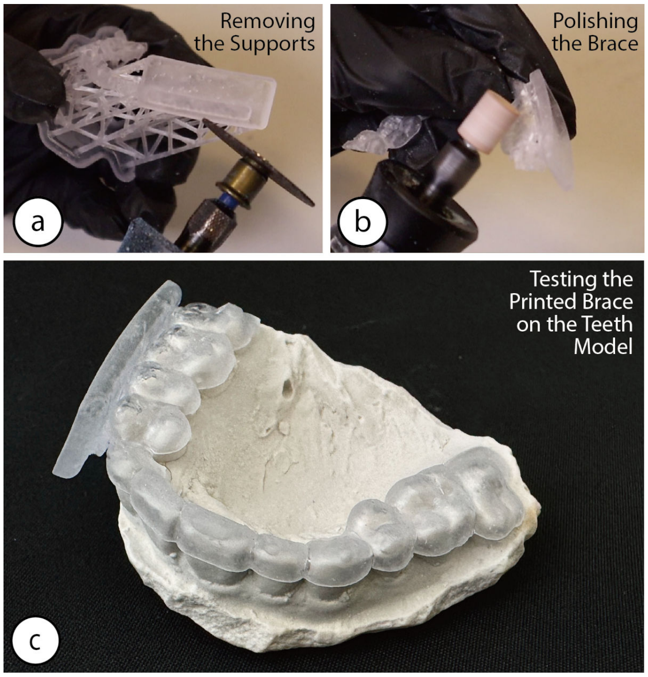

Figure 6: (a) Removing the supports from the printed brace, and (b) polishing it. (c) Testing the brace on the teeth model.

Fabricating the Flexible PCB. To make the flexible PCB, makers can either choose to fabricate it in-house by vinyl cutting[12] copper tape for fast iterative prototyping or have it fabricated by a commercial manufacturer at high quality. For in-house fabrication, makers first adhere the copper tape[13] on Kapton tape[14] (Figure 7b). The double-layer film is then attached to a base sheet[15] before inserting it into the vinyl cutter. We found that a force of 30 gram-force (gf) is sufficient for cutting only the copper layer (i.e., the trace), while 80 gf is optimal for cutting both the copper layer and the Kapton layer (i.e., the outline) simultaneously. Finally, makers can remove the cut-out copper using tweezers (Figure 7d).

Assembling. Once the circuits and the MouthIO braces are ready, makers can adhere the circuits to the housing base with a transfer paper[16] (Figure 8a) and proceed to solder all electronic components (Figure 8b), including the battery and microcontroller, onto the surface. During the prototyping stage, makers can apply the dental

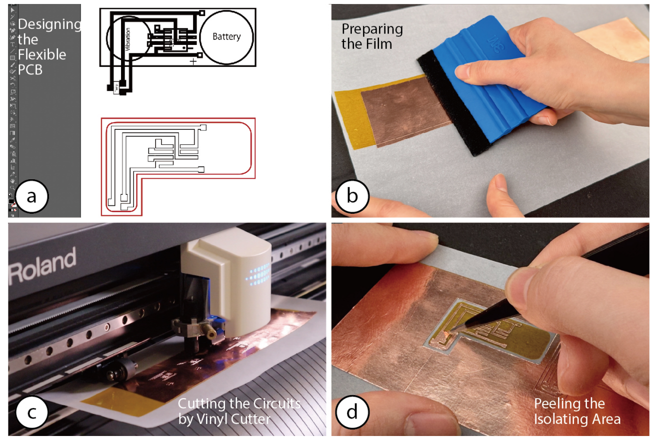

Figure 7: (a) Designing the flexible PCB in Adobe Illustrator. (b) Adhering the copper tape on the Kapton tape. (c) Cutting the circuits with the vinyl cutter. (d) Removing the cut-out copper using tweezers.

resin around the soldered connections to reinforce the adhesion of electronic components (Figure 8c), and cure it with a UV flashlight (Figure 8d). As an additional safety feature, makers should attach water contact indicators[17] to the PCB (Figure 8e). These indicators will change color if any moisture enters the PCB housing, serving as a warning system to indicate mechanical failure of the housing or inadequate sealing. Finally, makers can place the PCB housing lid on top of the housing base and seal it by applying dental resin on the edges (Figure 8f), then cure the seal in the UV curing chamber and wash it with isopropyl alcohol (IPA). If the design includes external circuit traces or components outside the PCB housing, makers should apply three resin layers to these components. Each layer should be cured before applying the next layer. Before wearing the MouthIO braces, makers can submerge them in water for 10 minutes and check on the water contact indicator if it changes color. Once the design is finalized, we suggest filling the entire PCB housing with dental resin to improve the structural stability.

4.5 Cleaning and Disinfection

MouthIO braces can be cleaned in the same way as commercial retainers. There is a large selection of retainer cleanser tablets commercially available that are dissolved in water and the user places the brace inside the cleaning solution for several minutes. Alternatively, users can clean them with a toothbrush and disinfect them with isopropyl alcohol (IPA).

To avoid food residues, we recommend removing the brace while eating similar to other commercial braces. When drinking beverages other than plain water, using a straw is recommended.

5 APPLICATION EXAMPLES

We present three application examples that showcase MouthIO's capabilities to monitor beverage consumption, monitor health conditions, and provide assistive technologies for users with motor impairments.

[12]CAMM-1 GS-24, https://www.rolanddg.eu/en/products/vinyl-cutters/camm-1-gs-24-desktop-vinyl-cutter
[13]Vegena Copper Foil Tape, 30m × 50mm × 0.05mm
[14]3M™ Polyimide Film Tape
[15]Tritart Tracing Paper, https://tritart.com/
[16]LOKLIK Transfer Paper, https://loklik.com/diy-tools
[17]3M™ Water Contact Indicator Tape

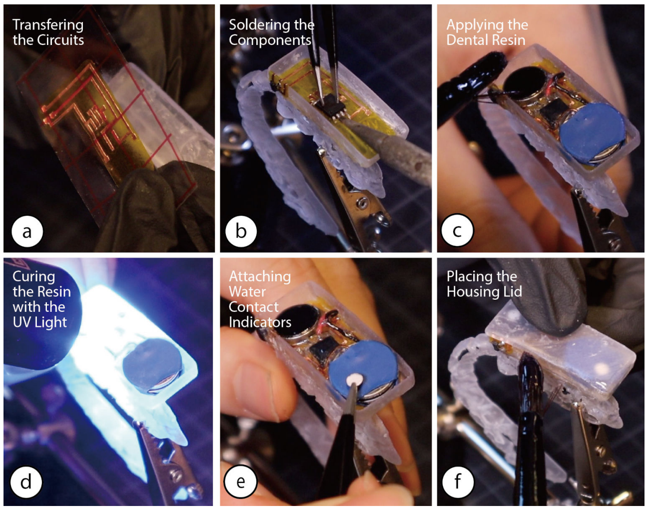

Figure 8: (a) Adhering the circuits to the housing base with a transfer paper. (b) Soldering all electronic components. (c) Applying the dental resin around the soldered connections, (d) and curing it with a UV flashlight. (e) Attaching water contact indicators. (f) Placing the PCB housing lid on top of the housing base.

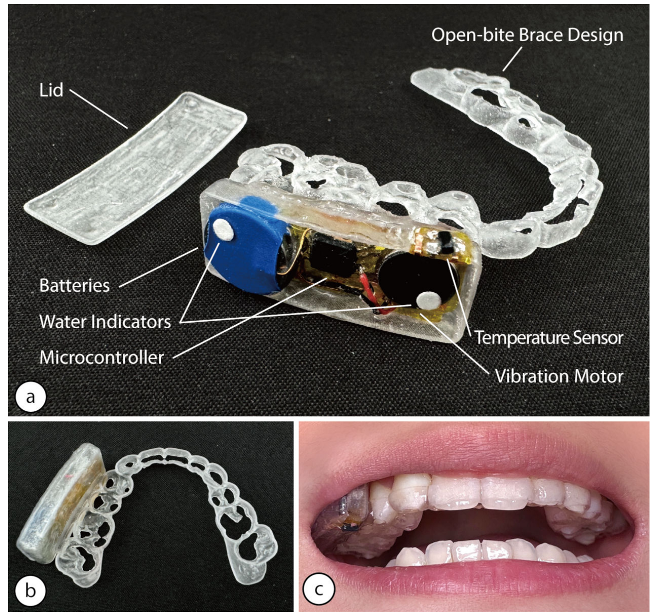

Figure 9: (a) The MouthIO interface with temperature sensor and vibration motor for monitoring beverage temperature, (b) with the lid on. (c) Wearing the MouthIO interface on the upper teeth.

5.1 Monitoring of Beverage Consumption

Users with oral hypoesthesia may experience numbness in the mouth due to entrapment of the lingual nerve [17], which can reduce their sensitivity to heat while drinking hot beverages. We created a MouthIO brace to detect high temperatures, providing an essential safety measure for users with this condition by integrating a temperature sensor on the braces that triggers a vibration motor to help users be aware of high-temperature beverages. Since The International Agency for Research on Cancer (IARC) assesses "very hot" (>65°C) beverages as "possibly carcinogenic" [5], the vibration motor is activated when the temperature sensor detects a temperature over 65°C. We chose the open-bite brace design for higher wearing comfort. The temperature sensor is placed on the bottom of the PCB housing to enable early contact with the beverage when the user drinks. We used dental resin to coat the temperature sensor fully. In the prototyping phase, we integrated an ATTiny85, two coin batteries, a temperature sensor (MCP9700), and a vibration motor into a 35mmx13mmx4.5mm PCB housing (Figure 9). We conducted testing by wearing the brace (Figure 1b) and drinking 75°C water, successfully activating the vibration motor. In the product stage, wireless charging can be implemented to enable long-term usage.

5.2 Health Monitoring

Bruxism is a widely occurring condition in which humans grind on their teeth in their sleep or even during awake times. Manfredini et al. [40] report that on average 12.8% of the population experience frequent bruxism. To support the diagnosis and monitoring of bruxism, we demonstrate a low-cost MouthIO solution that people can locally fabricate to monitor teeth grinding during sleep. We developed a MouthIO brace on the lower jaw as it is the primary moving component during grinding and integrated an accelerometer(ADXL345) to track jaw movements alongside a coin battery in 35mmx13mmx3.5mm PCB housing. We chose the closed brace design so that the braces can also act as a night guard, protecting the teeth from grinding during sleep. We added a wired connection to the prototype to generate continuous data for several hours and tested the prototype under three conditions: (1) biting, (2) grinding, and (3) no movement (Figure 11). The captured data shows that there are distinguishable patterns between these three stages that can be used to detect grinding. After confirming the functionality of the oral interface, the maker can add a larger capacity battery to enable data capture over several hours, along with a Bluetooth module to transmit the data wirelessly.

5.3 Assistive Technology for Users with Motor Impairments

Nearly 2 million people are living with limb loss in the United States [67], which may cause difficulty in using a keyboard or the touch screen of a mobile phone. Nguyen et al. [44] demonstrated that the tongue can accurately tap on multiple areas within the oral cavity. To support users with motor impairments in interacting with tongue-based user interfaces, we fabricated two capacitive touch pads located behind the upper teeth that can detect tapping with the user's tongue. During the prototyping phase, we embedded an ATTiny85, a battery, and two resistors (1MΩ, for capacitive touch sensing) into a 35mmx13mmx3.5mm PCB housing. We extended two copper traces on Kapton tape out of the PCB housing along the front teeth. Each of these traces connects to a 5mmx4mm pad which

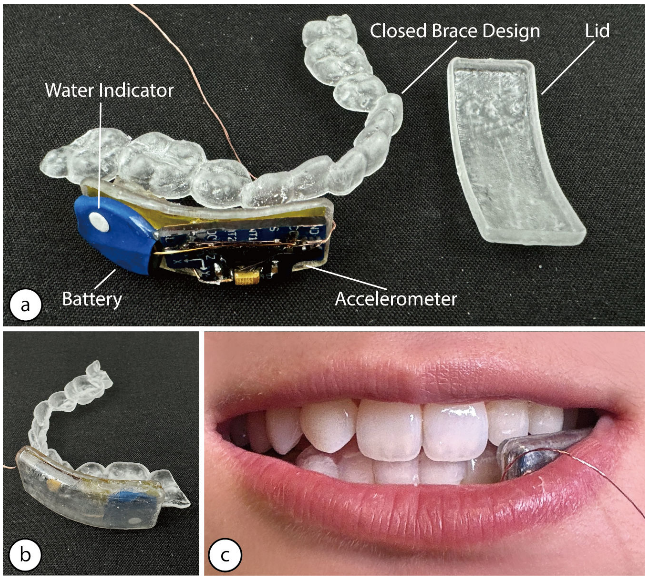

Figure 10: (a) The MouthIO interface with accelerometer monitoring grinding and biting, (b) with the lid on. (c) Wearing the MouthIO interface on the lower teeth.

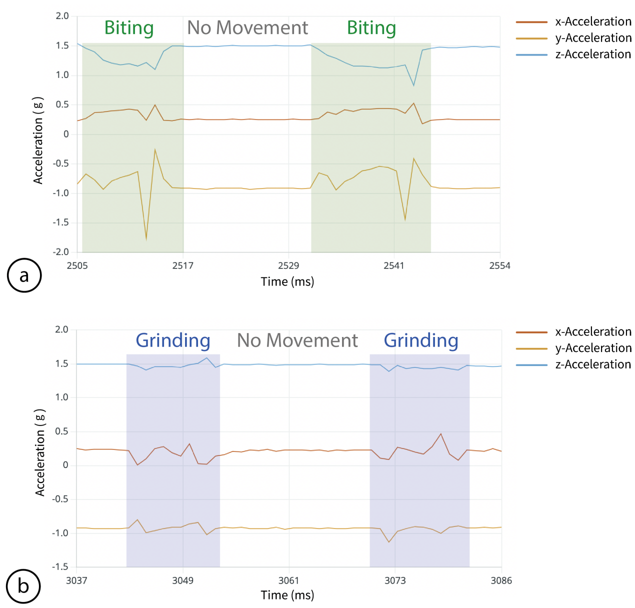

Figure 11: (a) Data showing acceleration patterns between biting and no movement captured while wearing MouthIO, (b) and acceleration patterns between grinding and no movement.

we located behind the left and the right front teeth (Figure 12b). We applied three coats of dental resin to the external circuits to ensure proper insulation. We added a wired connection to the prototype to access the touch data (Figure 12d). Once the maker confirms the functionality of the touch buttons, they can finalize their design by ordering and integrating a flexible PCB. In addition, they can make the final design mobile by adding a Bluetooth module and a wireless charging coil.

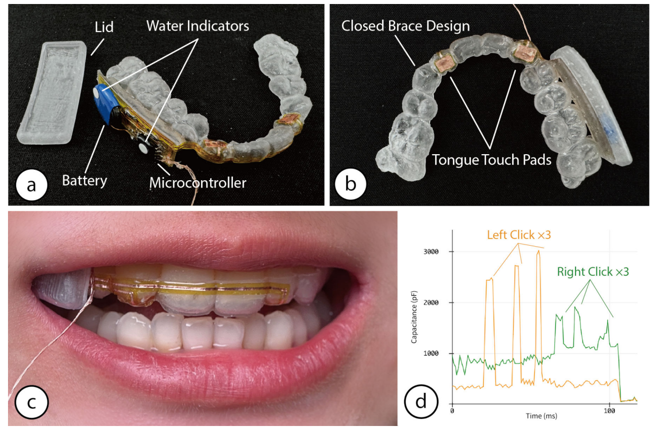

Figure 12: (a) The MouthIO interface with two capacitive touch pads for detecting tongue tapping, (b) with the lid on. (c) Wearing the MouthIO interface on the upper teeth. (d) Data showing the capacitive value pattern during tongue tapping on the touch pads.

6 TECHNICAL EVALUATION

We conducted an experiment on the structural stability of MouthIO's PCB housing to test its protection of the internal components against accidental bites.

Apparatus and Procedure. We printed five samples of an empty PCB housing and five samples of a PCB housing that we filled with dental resin. The empty PCB housing is used in our fabrication process for prototyping electronics. Once a brace design is final, we suggest filling the entire PCB housing with resin to improve the structural stability. This experiment compares both approaches. We placed each sample on a bend test device (Zwickroell Z005) and conducted a three-point bending experiment (Figure 13a) until we observed a complete structural failure. During the experiment, the machine moves with a constant speed down onto the sample while measuring the applied force to move further down. If the sample breaks, the required force drops instantly and the machine stops.

Results of the hollow PCB Housing Samples. Figure 14 shows the results of the experiment for the five hollow PCB housing samples. We observe three phases of deformation before the sample breaks. In the first phase, the originally curved PCB housing stays intact but gets bent until it is flat which requires between 52N and 73N while getting pushed down by 2.4mm. The second stage is characterized by internal compression of the PCB housing where the force stays nearly constant but the PCB housing gets compressed by 1.7mm. Once the PCB housing is fully compressed, we observe deformation until the breaking point which appears between 87N and 143N. Only the first phase protects internal electronics sufficiently. Since the average bite force of humans exceeds the safe

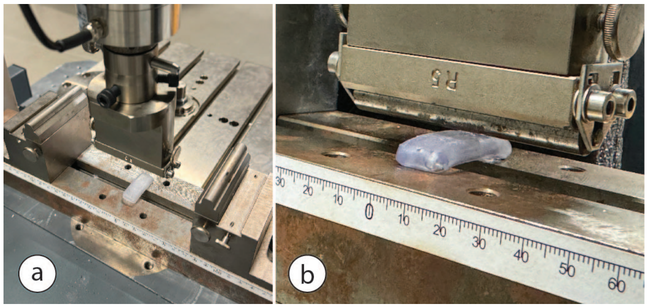

Figure 13: Pressure Experiment Setup. (a) We place the PCB housing sample in the center of the pressure test machine, and (b) press on the center of the PCB housing to conduct a three-point pressure test until full structural failure.

force range at 285N [55], it indicates that the hollow PCB housing is only suitable for iterative prototyping where the user has to handle the MouthIO brace carefully.

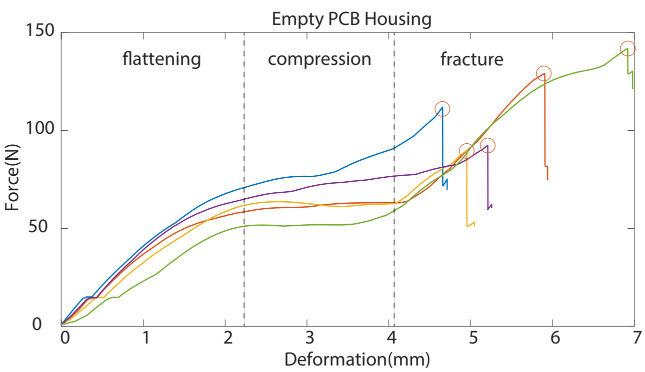

Figure 14: Pressure Experiment with an empty PCB housing. We see three stages in the force profile. First, the curved housing gets flattened which leaves internal electronics intact. Second, there is a compression phase where the housing gets squeezed together until it is fully squeezed together and starts bending again in the third stage until it fully breaks.

Results of the solid PCB Housing Samples. Figure 15 shows the results of the experiment for the five solid PCB housing samples. We observe two phases of deformation before the sample breaks. In the first phase, the PCB housing linearly deforms with the applied force. At 2mm deformation, we see an increase in the necessary force to deform the sample. A possible explanation for this behavior is internal air bubbles in the sample that remain after putting the housing lid on the housing base and that get pushed out in the first phase. The five samples show an inconsistent magnitude of force for the breaking point. The weakest sample broke at 662N while the strongest sample broke at 2173N. We hypothesize that this variation in the results can be explained by 3D printing inconsistencies. However, even the weakest sample showed that when the average bite force of humans is applied (285N [55]) only a deformation of 1.4mm occurs while the strongest sample only deformed by 1mm.

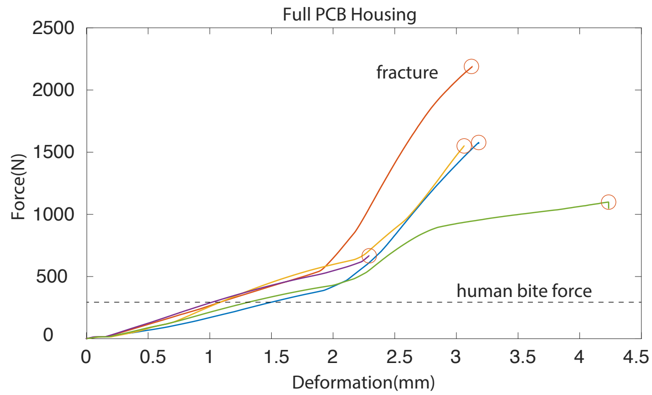

Figure 15: Pressure Experiment with PCB housing full of resin. The housing breaks between 662N and 2173N which is above the adult bite force (285N [55]).

7 USER STUDY

To investigate the impact of MouthIO interfaces on the users' daily lives, we conducted a user study focusing on the acceptance and wearability of these braces. We seek to understand user experiences, expectations, and limitations when wearing oral interfaces. In addition, we evaluate the two proposed brace designs (Figure 2) with regard to comfort and user preferences.

The study is designed to examine four main goals that contribute to our understanding and development of in-mouth interfaces:

- Comparison of the closed and the open-bite designs regarding comfort and user experience.
- Evaluation of wearability over extended periods, focusing on aspects such as comfort, design, and ease of use.
- Investigation of social acceptance, considering factors like aesthetics, social interactions, and the potential for adoption in everyday settings.
- Identification and categorization of application scenarios, highlighting user preferences and needs.

These goals guide our user study, ensuring a comprehensive understanding of our designs' impact from multiple perspectives. Our study conforms with the ethics regulations at our institution and our study protocol was approved by our institution.

7.1 Methods

The study consisted of two subsequent parts. The first part compared the two designs of the brace (closed and open-bite design) with regard to comfort and articulation, while the second part examined the wearability and social acceptability of the brace of the user's choice.

Participants. We recruited ten participants (8 male, 2 female) from our workplace and wider network, ages 22-35 (M=26). Four of them indicated prior experience with dental devices, such as metal braces and orthodontic plastic retainers. We excluded participants with ongoing dental treatment and current dental diseases.

Apparatus. We fabricated personalized MouthIO braces for the study participants after taking their teeth mold in a preparation session. In place of the circuits and battery, we 3D-printed the PCB housing with a size of 35mm x 13mm x 3.5mm, which is big enough to hold an ATtiny85 microcontroller, a CR1220 3V battery and a few electronic components, like a vibration motor or SMD components. We filled the PCB housing completely with resin to simulate the weight of the internal circuitry (see Figure 2).

Procedure of Study Part A. Each participant received their individual braces in the two different design variants, i.e. the closed design and the open-bite design.

They were instructed to wear each brace variant for ten minutes while carrying out two tasks. For the first task, participants were asked to drink water from a bottle to observe their experience of beverage consumption as in application example 5.1. The second task was aimed at evaluating lingual articulation with the different brace designs. Participants were asked to read a text passage [18] out loud, which is used in speaking evaluation with braces and lingual orthodontic therapy speech research [46, 51].

After wearing the brace design from each condition, participants were asked to fill out a questionnaire indicating the comfort of wearing the brace generally and while drinking and reading aloud. Questions were adapted from the Technology Acceptance Model (TAM) [15] and from key dimensions identified in the TAM [52]. Each participant was asked to choose their preferred design, which they then used for the second part of the study.

Procedure of Study Part B. For the second part of the study, participants were instructed to resume their daily activities while wearing their chosen brace design, while engaging in social interactions with other people.

After at least 24 hours, participants returned to the lab and answered a final questionnaire regarding the wearability, comfort, and social acceptability of the brace. This was adapted from the WEAR scale for the evaluation of social acceptance of wearable devices [30], to which we added questions specifically aimed at understanding the experience of wearing oral interfaces. Measures were rated by the participants on a 7-point Likert scale [39] ranging from *Strongly Disagree (1)* to *Strongly Agree (7)*. Subsequently, we conducted a semi-structured interview on user perceptions of durability, comfort, and acceptance.

7.2 Results of Study Part A

Closed vs. Open-bite Design. Eight out of ten participants chose the open-bite design as their preference for the second part of the study. Reasons for choosing the open-bite design given in the initial interview include a more natural tactile feeling, less hindrance in talking and less pressure on the teeth.

The feeling of naturally touching the upper and lower front teeth was named as a reason for the natural feeling; P8 mentioned they "*find it easier to say those syllables like 's'*" with the open-bite design, while P6 mentioned the coverage of the front teeth as a drawback of the closed design: "*I can't feel the edge of my teeth with my tongue.*" While the open-bite design was described as "*more subtle*" (P6), "*more real*"(P6) or "*more comfortable*" (P8), the closed-bite design was reported to feel "*more tight*" (P3&P10) and "*bigger and bulky in my mouth*" (P6).

The two participants who chose the closed design reported this was due to water and saliva filling the open-bite design more easily, as well as the tongue getting stuck in the gap between the brace and the front teeth of the open-bite design.

Two participants who had worn braces before indicated that the closed design was comparable to the clinical retainer they wore after treatment with metal braces. They described the feeling while wearing as familiar, yet mentioned the open-bite design as an improvement to these full-coverage aligners, such as P5 who stated that "*especially because the bottom was cut off, it was a lot more flexible than those you get from the dentist. So I think that was a really nice choice.*"

Participants answered the question if drinking felt natural with a median of 7 (AVG=6.4; SD=1.26) for the open-bite design and with a median of 6 (AVG=6.1; SD=0.88) for the closed design. While P10 reported they can feel the water more on the teeth due to the open-bite design brace, P2 and P9 describe the feeling as quite normal.

Reading out loud was rated by the participants as feeling slightly natural with a median of 5 for both designs (AVG=4.7; SD=1.89 for open-bite design, AVG=4.7; SD=1.42 for closed design)). P1 reported on the open-bite design "*I can feel there's something in my mouth, but it does not influence my communication*", while P2 experienced that "*it's a little bit different. Different, but I would say it does not affect [talking] that much.*" Three participants mentioned they prefer the open-bite design for speaking, as they can feel the front teeth more.

Overall, the open-bite design was preferred by participants for its enhanced control over the front teeth, the more natural feel and its comfort. This preference underscores the importance of user experience in brace design choices, emphasizing the open-bite design's positive impact on everyday activities such as speaking.

7.3 Results of Study Part B

Wearability. In the post-study interview, participants reported wearing the selected brace design for an average of 6.9 hours (min 2h, max 20h) during the study day. Some participants stated that the brace feels "*just really comfortable*" (P5) and "*quite normal*" (P4). P8 reports that "*In terms of pain or discomfort, I didn't really feel anything that much.*" None of the participants reported the brace getting damaged, becoming loose, or sliding down from the upper teeth during extended wear.

Other participants reported the feeling of tightness or light pressure on the teeth, as P2 states that "*It's a little bit tight. But it's okay.*" This tightness of the brace could create more awareness for it; P8 for example reports that "*Most of the time I'm just aware. [...] I have to adjust a little bit.*"

In the post-study questionnaire, participants rated getting used to the brace with a median of 6 (Agree) (AVG=5.3; SD=1.34). In the post-study interview, P8 mentioned they "*didn't really feel anything that much. Maybe in the initial few hours, there was an adjustment period, after that [it] was fine.*" All participants reported in the interview that they got used to the brace on some level, and some even "*subconsciously forgot about it*" (P7). Verbal articulation with the brace was also found to increase over time, as P5 states "*The more I wore it, the easier it was to talk with.*"

In the post-study questionnaire, experiencing discomfort or pain while wearing the brace was rated by participants with a median of 3 (AVG=3.3; SD=1.06), which responds to weak discomfort or pain. This was mostly due to the PCB housing, which caused mixed experiences with participants reporting feeling it not at all (P6), only when thinking about it (P3, P7 & P10), and all the time (P1, P2 & P4). Reasons for uncomfortable sensations included the placement and size of the compartment as well as the inflexible material. From what participants mentioned, we find that the compartment size and placement depend on their individual jaw geometry, as it can interfere with jaw muscle movements like smiling. As these experiences were highly individual, the location of the compartment needs to be personalized to ensure comfort for all individual jaw geometries. During the interview, four participants mentioned that the sharp edges of the brace could cause tongue friction. This feedback indicates that carefully polishing the edges of the brace is crucial and may significantly improve comfort.

Participants took the brace out to take breaks, which they considered important to maximize comfort in long-term wearing. Six participants mention taking breaks as a possible strategy to increase wearing time. Overall, participants report individual imaginable maximum continuous wearing times ranging from 2 to 24 hours.

Despite recognizing the potential for comfort improvements by relocating the PCB housing, the feedback on wearability was largely positive. Users appreciate the device's overall comfort and point out that it becomes increasingly wearable over time. This adaptability suggests that with minor adjustments, the device could offer a seamless and comfortable experience for prolonged use.

Social Acceptability. Participants of the post-study interview reported the brace as highly socially acceptable. It was perceived as not lowering confidence when interacting with other people. In the post-study questionnaire, the "coolness" of the brace was rated with a median of 6 (AVG=5.7; SD=0.95), while participants also rated that the device could be considered a normal part of life with a median of 5 (AVG= 5.2; SD=1.03).

Five Participants report noticeable reactions of their peers and describe these as interest without any negative judgment. P3 for example experienced reactions which were "*definitely curious. Not bad*", while P4 also mentions curiosity about the purpose of the brace.

Two participants mentioned taking the brace out for important work meetings, voicing doubts about acceptance in customer meetings (P7) and that wearing it on these occasions "*might be a bit weird*" (P2). Nevertheless, apart from these instances, the participants mentioned they would still wear the brace to work.

P6 experienced that while wearing the brace at work in a meeting, "*there were no comments on it.*" The braces were in two incidents perceived as aligner braces by the participants' conversation partners. Other participants reported that no one noticed while talking to bigger groups of people (P1) or that at least nobody reacted (P10). P3 even mentions a positive feeling of technology enthusiasm and a futuristic self-image while interacting with others while wearing the brace in the mouth.

In the post-study questionnaire, participants were asked to complete the comprehensive WEAR scale to assess the social acceptance of wearable devices. Upon thorough analysis, we selectively reported on a subset of these questions. This decision was informed by the majority of responses suggesting a neutral stance with minimal variance. Consequently, our focus was directed toward questions that yield more actionable insights into user perceptions and acceptance levels.

Overall, participants found the brace to be highly socially acceptable, noting that it did not detract from their confidence during interactions. The device was considered a potentially normal part of life, with the only reactions from peers being ones of interest.

Application Scenarios. Responses given by the participants in the post-study interview reveal that the greater the perceived benefit of the brace, the more inclined individuals are to wear it, and importantly, for extended periods. Participants shared wishes, ideas and requests for functionalities and applications of the device, ranging from supporting disabled individuals, health monitoring, subtle or hands-free interaction, to more personalized ideas and artistic endeavors like creating music.

P2 for instance imagined the MouthIO brace monitoring their dental health and indicating "*the health condition of my mouth, my teeth, or if I have a bad breath.*" P4 voices similar ideas, as having a possibility to monitor bacteria in the mouth and possibly releasing medicals to react to imbalances in oral health.

Four participants mentioned hands-free interactions, such as controlling wheelchairs (P1, P9), skipping presentation slides (P3), controlling home appliances while doing housework (P6), gaming and interacting in Augmented and Virtual Reality (P9) or initiating communication through tongue touches (P7).

Two participants emphasized the possibility of using the anonymity and subtlety of in-mouth touch sensing. P6 shared they liked the invisibility of interactions within the mouth for "*some sort of scenario where I didn't really want other people to notice it [. . .] or it would be inappropriate to pull out a phone.*" They summarized the wish for a subtle or hidden form of communication which P7 shares: "*something you can do with your tongue that no one can see [. . .] If someone wants to tell me something without either waving or texting or calling or blinking or anything, you can receive something through the mouth, like for example heat.*"

Participants further envisioned innovations spanning from practical health and safety solutions such as sleep monitoring for snoring and bruxism (P3) alongside food consumption aids like spice measurement and water quality detection (P5). They also considered emergency scenarios, proposing discreet call functions for individuals feeling unsafe (P4), as well as the creation of tactile sensations in the mouth (P7). Participants also suggested speech improvement tools, focusing on lisp and hesitation detection, and managing language speed (P3), showcasing a broad spectrum of possible applications.

The diversity of ideas in the interview underscores that applications that resonate most with an individual's needs and interests are the ones that significantly increase their willingness to integrate the device into their daily lives for a longer duration.

7.4 Insights gained from the User Study

Results from the user study indicate a positive reception towards the brace, with participants finding it innovative and comfortable enough to be worn for extended periods with breaks. The innovative open-bite design was highlighted as a novel feature that could introduce significant improvements to traditional brace designs, suggesting potential benefits in both functionality and user experience.

It was particularly important to generate insights on the acceptance of in-mouth interfaces. How information technology innovations are received can be significantly influenced by real or perceived disapproval from others [35], making it crucial for these technologies to be socially accepted [58]. The results of our study indicate a generally positively perceived social acceptability of the braces, suggesting that this kind of device can be worn in daily life without negative reactions of others.

The mixed feedback on the placement of the PCB compartment, as well as individual insights to comfort and wearing patterns indicate a high need for individualisation. Different jaw geometries need to be accommodated when manufacturing braces. The proposed MouthIO design tool (Section 4.3) takes this need for individualization into account and approaches the creation of in-mouth interfaces from a personalization-focused angle.

As some participants voiced a feeling of tightness around the teeth, we want to investigate alternative material options to account for wishes for a softer brace. The Formlabs Dental LT Comfort Resin[18] as introduced in early 2024 might offer higher comfort for creating softer oral devices that we plan to evaluate in a future iteration on wearability and comfort.

Insights from our study reveal that users adapt to wearing the brace over time, highlighting the potential for improved comfort and wearability with extended use. This observation underscores the need for a future long-term wearability study to explore the full implications of prolonged use, including user adaptation and long-term comfort.

The users' wish to utilize the device increases with its benefits and perceived need for specific applications, indicating that user willingness is significantly influenced by the perceived value and utility of the technology. As our user study investigated perceptions and experiences towards the braces with non-functional braces, we aim to explore the wearability and user scenarios of fully functional in-mouth interfaces in the course of future work.

8 DISCUSSION

MouthIO demonstrates the first multi-purpose intraoral user interface that can be fabricated at low cost by dental technicians, researchers, and experienced makers. Still, there are several opportunities for future research on oral interfaces around form factor, integrated power supply and wireless communication, as well as MouthIO's fabrication process.

Portability with Wireless Communication and Recharging. Placing batteries in the mouth is still a challenge for safety. One possible option are silver oxide batteries, which are already used in some in-body medical devices, such as colonoscopy cameras (Pillcam™ Colon 2[19]). Recent advances on rechargeable sodium-ion batteries might provide more safety than lithium-ion batteries but research is still needed to evaluate their properties for wearable and oral application scenarios. In addition, wired power and communication are the main reasons that limit the long-term monitoring with wearable devices. Similar to [14], we plan to add a wireless recharging coil to our MouthIO braces after integrating rechargeable batteries to improve on its reusability. In addition, several studies have proposed solutions for wireless communications, such as triboelectric mechanisms [60], soft solid batteries for on-body power generation [9] and near-field communication (NFC) [12]. Therefore, combining these technologies with MouthIO will increase its long-term usability and open up new application scenarios for a broader audience.

Single-sided MouthIO on Molar Teeth. We experimented with a MouthIO prototype that is only attached on one side of the jaw on the molar teeth (Figure 16). This design has the advantage of being almost invisible and might provide more comfort than the designs presented in this paper. Since the front teeth are not covered with any material, it also reduces lisping. However, the brace is small enough to be a potential choking hazard if not permanently affixed to the teeth. This could be achieved by using dental glue or placing a magnet on the molar teeth similar to Huo et al. [26]. In the future, we want to explore this design further when it is more securely attached to the teeth.

Figure 16: Single-sided MouthIO brace. The braces are only attached to one side of the molar teeth which leaves the front teeth free. This might avoid lisping as the front teeth are not covered with the braces.

User Study on Multiple PCB Housing Sizes and Locations. Our user study focused on a single-size PCB housing (35x13x3.5mm). In the future, we want to conduct a comparative study on different PCB housing dimensions. Depending on the application scenario, the PCB could be even smaller reducing the size of the PCB housing or larger sensors could be integrated if an increase in the housing dimension is tolerable by users. Our user study also demonstrated that the location of the PCB housing plays a significant role in the comfort of wearing a MouthIO brace and a future user study on the

[18] https://formlabs.com/eu/store/dental-lt-comfort-resin/

[19] https://www.medtronic.com/covidien/en-us/products/capsule-endoscopy/pillcam-colon-2-system.html

housing location could indicate more optimal locations depending on the user's teeth geometry.

Automated Scanning and Mesh Processing. We presented a design and fabrication process that still relies on several manual steps that might pose a challenge for novice makers. Users have to obtain a digital model of their teeth which we currently achieve with a manual molding process. This process is time-consuming and relies on a mobile phone app for obtaining a digital model. A future alternative is handheld scanning devices already used by dentists (e.g., 3Shape Trios 5[20]) but is still expensive (≈ $15k) and not commonly available in maker spaces. An additional manual step is the cleaning of the digital mesh from the gums and fine-tuning the location and size of the PCB housing. We want to explore an automatic teeth segmentation algorithm [13] to analyze individual teeth, generate custom braces and PCB housing automatically.

9 CONCLUSION

We presented MouthIO, the first user interface within the oral cavity that can be customized in form and function. By using our design and fabrication technique, dental technicians, researchers, and experienced makers can fabricate intraoral user interfaces with various sensors and actuators. We demonstrated the working principle of MouthIO and showcased its application examples in beverage consumption monitoring, health tracking, and assistive technology, with the integration of temperature sensors, capacitive touchpads, and accelerometers. Our user study has demonstrated that MouthIO is suitable for extended wear over multiple hours and is highly socially acceptable. The technical evaluation demonstrated that the 3D-printed PCB housing can withstand the bite force of adults. For future work, we aim to enhance MouthIO by incorporating features such as Bluetooth communication and wireless charging, as well as investigating the feasibility of printing the brace with flexible dental resin. Additionally, we intend to conduct a long-term user study with a functional MouthIO interface involving electronic components, to observe prolonged wearability and utility.

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