Custom mouthpieces for dental care

Design for manufacturing of custom toothbrush mouthpieces.

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01. Summary

This report covers the design, implementation, and manufacturing methodology of a custom mouthpiece for the Air One toothbrush in development by Dental Robotics. The results are a proof-of-concept digital processing pipeline, a functional prototype, an evaluation of custom mouthpiece efficacy relative to the standard mouthpiece, and a recommended manufacturing setup.

1.1. General information

The standard mouthpiece used by Dental Robotics is not wholly capable of effectively cleaning the interdental regions of individuals. This report proposes a manufacturing concept through which mouthpieces can be produced based on dental scans of the user, seeking to improve on the original mouthpiece in terms of interdental performance and fit.

1.2. Development timeline

The manufacturing process is designed to be implemented over a period of six months. This includes possible exploration of alternative actuation methods, implementation of the software automation, and manufacturing setup.

1.3. Production process & costs

The custom mouthpiece consists of two main components. The frame, which conforms to the shape of the user's teeth and controls the actuation behaviour, is manufactured using FDM printing of food-grade TPU. The bristle sheet, which guarantees airtightness and supports nylon bristle tufts, is thermoformed onto the frame and attached using vapour solvent welding.

Preliminary estimates put the manufacturing costs at about 3.5 euros per piece (or a consumer price of around 15 euros), with initial design costs of around 40 euros (for a consumer price of around 60-80 euros). At this price point, the mouthpiece is highly competitive with alternative products, which offer either lower levels of personalisation or higher prices.

1.4. Future recommendations

While this implementation of the mouthpiece is shown to be viable and effective, it is recommended both to explore the efficacy of simpler (non-actuated) alternatives, and to optimise details such as bristle length, base geometry, and mouthpiece width and depth before beginning manufacture.

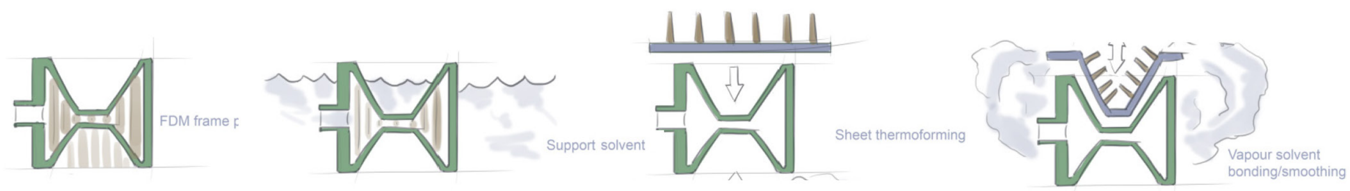

Figure 01. Manufacturing overview

Figure 02. Render of the Dental Robotics custom mouthpiece in combination with a standard handle.

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Section 1 - Analysis

Section 2 - Synthesis

Section 3 - Detailing

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03. Introduction

The standard mouthpiece of the Air One does not clean plaque optimally for all dental anatomies. Partly, this is caused by the imperfect fit of a one-size-fits-all mouthpiece. This design assignment intends to find a manufacturing methodology and process which allows custom mouthpieces to be tailored to individual dental forms.

This report covers the development and implementation of a custom mouthpiece for the Air One, a pneumatically actuated toothbrush currently in development by Dental Robotics. The focus of the design process revolves heavily around manufacturing.

This report is divided into sections governing general market research, dental anatomy, pneumatic actuation, ideation of working principles, design automation, and manufacturing detailing.

Aside from this report, the results of the project include a proof-of-concept workflow for the automatic processing of dental scans and a functional prototype manufactured mostly according to the chosen principles.

This introductory chapter discusses Dental Robotics as a company and the project design brief.

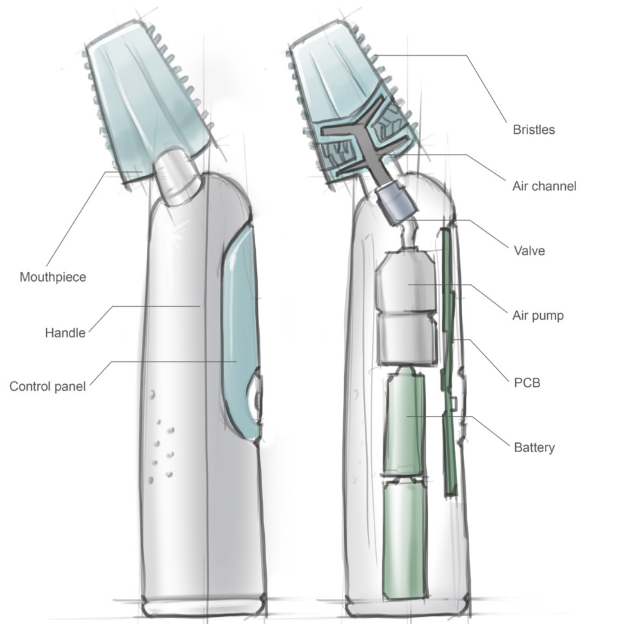


Figure 04. Dental Robotics Air One

3.1. Dental Robotics

Dental Robotics is a Delft-based start-up, founded in 2017 by Joppe van Dijk, developing a pneumatically actuated toothbrush. At the time of writing, the product is in the late stages of development, with experimental deployment planned in several months.

The company consists of around twenty employees, many of them (graduation) interns. After about two years of development, available resources include extensive 3D printing and prototyping facilities, injection moulding machinery, and a close cooperative relationship with an injection moulding manufacturer.

3.1.1. Air One

The brush, currently under development under the placeholder name 'Air One', is supposed to enable faster, more reliable cleaning than traditional toothbrushes. Unlike some similar concepts of full-mouth toothbrushes in recent years, Dental Robotics have chosen initially to aim their product at the elderly care market. The fact that this product can increase dental care efficiency is a major advantage for caretaking institutions.

3.1.1.1. Functionality overview

The toothbrush consists of a handle with an air pump/ valve system, PCB, and battery, and a mouthpiece which can be connected to the handle. The mouthpiece, a flexible component with bristles, fits around the teeth of the user and acts as a pneumatic actuator, inflating and deflating for a short period. This cycle causes the bristles to make contact with the user's teeth and clean the surface of plaque.

The production model contains bristles cast as part of the TPE actuator, although the company have expressed a desire to switch to traditional Nylon bristles once the manufacturing process allows it.

The full-mouth actuation process is intended to speed up the process of cleaning (with a target of ten seconds, as opposed to the two minute minimum for conventional toothbrushes), while also improving the consistency of the cleaning quality (compared to manual brushing by inexperienced users).

3.2.1.2. Limitations

Currently, the standard mouthpiece typically cleans around seventy per cent of plaque – with most of the remaining plaque being concentrated around the ‘interdental’ regions and the contact line between the gums and the teeth.

The mouthpiece is designed as a compromise between efficacy and comfort. This means that the length of the arch is not enough to reach every molar in most dental shapes. The resulting lack in reach is mitigated by moving the mouthpiece sideways while brushing.

As the mouthpiece is a one-size-fits-all design, it typically performs and fits worse for users with unusual dental anatomies.

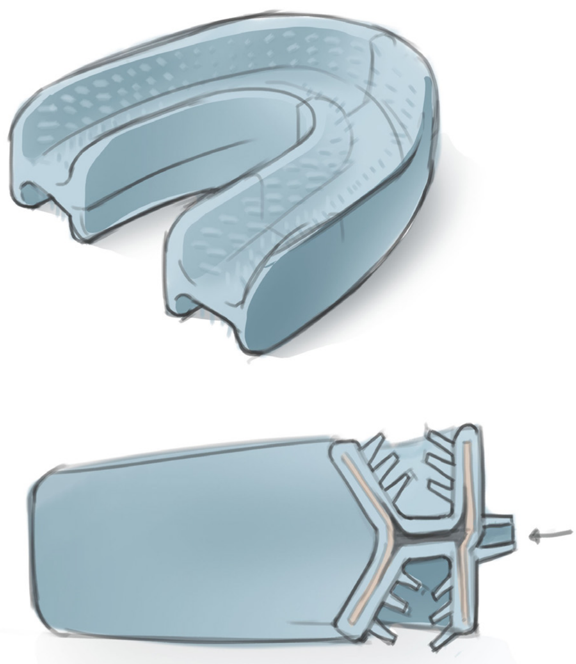


Figure 05. Mouthpiece overview. Blue is flexible TPE, orange is rigid material.

Figure 06. Overview and cross-section detail view of the Dental Robotics Air One.

3.2. Design Brief

This subsection interprets and expands on the initial design brief. The full design brief as entered at the start of the project can be found in the appendix, section 3.

The goal of this project is to design a data processing and production workflow which can be used to produce and sell custom versions of the mouthpiece. These mouthpieces are to be based on 3D scans obtained from the user, with geometric changes to improve the cleaning properties of the toothbrush.

As a relatively late-stage design assignment, by the end of the project the product should be demonstrably effective, producable, and viable.

Its effectiveness should be demonstrated such that, at least for a subsection of Dental Robotics' clientele, the custom version of the mouthpiece is capable of being effective in cleaning plaque than the standard mouthpiece. The production requirements are considered to be met when it can be produced in such a way as to maximise possible geometric adaptations as well as cost effectiveness. Viability is defined by the extent to which it is attractive in terms of functionality, aesthetics, and price point, to the target audience, and as such manages to position itself in the market.

3.2.1. Design goals

By the end of the project, the following design goals have to be met:

- Determining the geometric changes which can be made to improve the performance of the mouthpiece on a particular set of teeth.

- Selecting a manufacturing method which finds the optimal balance between manufacturing costs and individual geometric freedom.

- Developing a processing pipeline which enables 3D scans of individual patients to be converted to corresponding mouthpieces with minimal human intervention.

- Demonstrating the effectiveness of all of the above using a prototype which adheres as closely as possible to the established manufacturing methodology.

3.2.2. Constraints

A basic list of constraints for the product is available a priori, based on criteria set by the company.

- Final product price should not be higher than that of competing full-mouth custom toothbrushes, both in terms of design costs (~200 euros) and unit price (~25 euros)

- Plaque removal should be superior (in terms of surface percentage) to the standard mouthpiece in anatomically deviant cases, and superior near the interdental regions in all cases.

- The product should be developed, both in terms of design and manufacturing, to the point where it can enter production within twelve months from the graduation date.

- At the end of the project, it should be possible to create a prototype mouthpiece from a given set of teeth within the established geometric boundaries, and demonstrate its effectiveness.

- Manufacturing ramp-up should be possible within approximately 6 months from graduation

Detailed product requirements are outlined in chapter 6, based on contextual research.

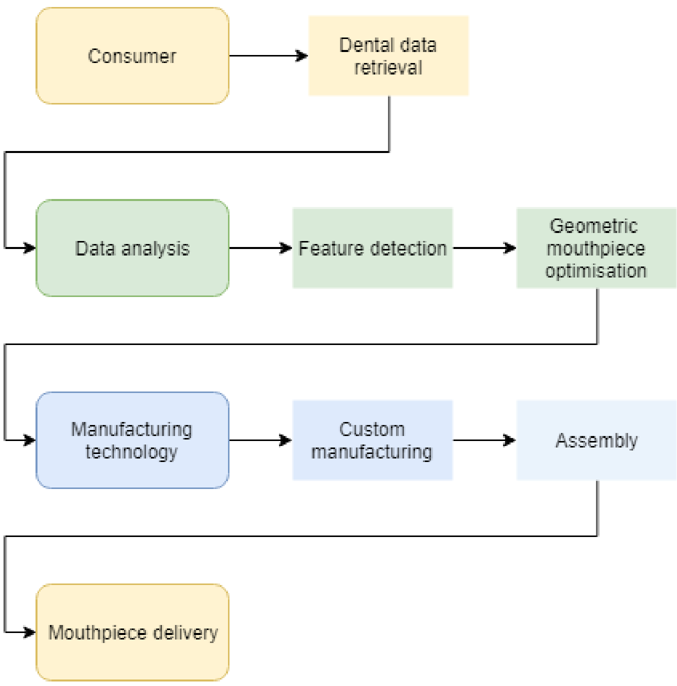


Figure 07. Process outline: dental data is received, processed, and used for mouthpiece manufacture.

3.2.3. Timeline

Allowable manufacturing methods and complexity are dictated by the 6-month post-graduation implementation time. The timeline of both the graduation itself (table 1) and the post-graduation trajectory (table 2) are subdivided accordingly to fit this timeline.

Context research and design automation are essential parts of the project, but are kept relatively brief in favour of ideation and manufacturing. These latter topics demonstrate the essential viability of the product, which can be considered the first priority of this project.

Month number	1	2	3	4	5	6
Research	Context: medical / market / actuation					
Ideation	First iteration	Second iteration / third iteration	Third iteration / prototyping			
Data analysis			Dental processing	Geometry generation		
Manufacturing				Method selection	Selection / development	Final prototype / validation
Reporting			Midterm report		Greenlight report	Report / presentation

Table 01. General schedule of the graduation project. For a week-by-week split, see appendix section 3.

Post-graduation scheduling, being constrained by a very narrow time limit, is dependent on the various components of manufacturing being independently developable. Validation of the manufacuturing method can happen simultaneously with further development of model automation. Manufacturing can be finalised as a distribution and partner network is being established.

This way, the project implementation is only limited by a few major obstacles: validation of the optimal manufacturing method before the manufacturing testing begins, and in-vivo performance evaluation before product partners can be introduced.

The details of the post-graduation schedule are based on the manufacturing method chosen in subsequent chapters, but may vary based on the results of manufacturing validation.

Month number	1	2	3	4	5	6
Validation	Alternative actuation exploration	In vivo effectiveness validation			Generator consistency/ range	Test sequence
Automation	Dental segmentation refinement		Geometry generation refinement			
Manufacturing		Material test - extrusion	Material test - printing / processing	Material test - thermoforming	Manufacturing setup	
Distribution			Dentist partner program	Partner acquisition	Partner acquisition	Partner acquisition

Table 02. General schedule of post-graduation implementation trajectory.

04. Market Context

The dental care market is a highly saturated one, although the proposed market segment for the custom toothbrush has not yet been satisfied. Compared to the standard mouthpiece, the higher price of the custom toothbrush may require a more health-oriented marketing compared to toothbrushes in the beauty or convenience segments of the market.

This chapter covers the context in which Dental Robotics operates, and in which the custom mouthpiece will be developed. Topics include the history of the electric toothbrush, stakeholder analysis, and an overview of the competition.

4.1. Electric Toothbrush History

While the electic toothbrush as we know it is a relatively recent invention, its predecessors go all the way back to the 19th century. This extensive history is important in order to understand the current cultural significance and connotations of the electric toothbrush.

Like most medical inventions and innovations, the history of the electric toothbrush starts with quackery. The 19th century "Dr. Scott's Electric Toothbrush" did not, in fact, contain any electronic components, nor was it advertised as having any electronic features: it simply relied on the buzzword 'Electric' being new and exciting to bolster sales (American Artifacts, 1998).

Early models of electrically actuated toothbrushes were patented and fabricated as early as 1939, although their popularity was so low that the products seem to have escaped almost all public notice (Mosely, 1937).

The first commonly available electrically actuated toothbrush was sold under brandname Broxodent in 1959, and suffered in popularity due to running on live wall socket power. Its most notable successor, built by GE, was rechargeable and wireless. This improvement was held back somewhat by it being only 1961, meaning the NiCad batteries—and with them, the entire toothbrush—became useless rather quickly, and took up a not-insignifcant part of the entire bathroom (Mayer, N.D.)

The toothbrushes were often, as they are now, marketed as 'more effective' than their manual counterparts, with particular emphasis on patients with reduced motor skills.

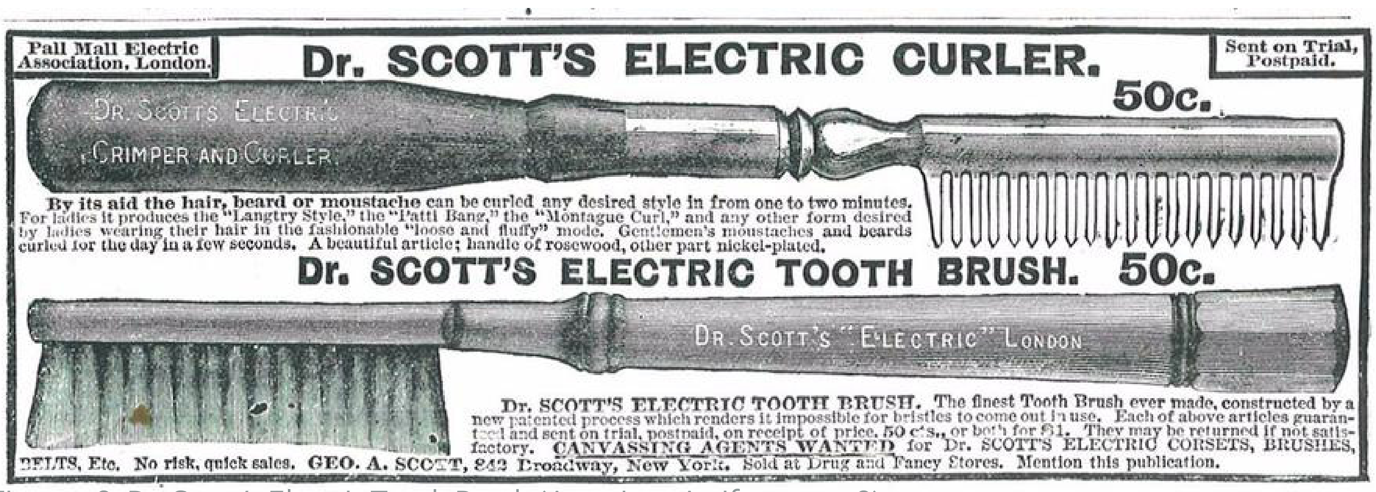


Figure 08. Dr. Scott's Electric Tooth Brush (American Artifacts, 1998)

Following improvements were incremental, until in the 1990's line voltage toothbrushes were banned completely. 1992 also saw the introduction of piëzo-crystal actuated ultrasonic toothbrushes (Haynes-Kershaw, 2007). These brushes actuate at frequencies beyond the limits of human hearing, but have not been convincingly demonstrated to provide any benefit.

The early 2010's saw the introduction of Bluetooth connectivity for the Oral-B Genius and Pro series, mostly intended to entertain the user while brushing, and more heavily supporting the 'beauty' audience of the market segment (Kampbell-Dollaghan, 2014). These brushes often include some kind of feedback element, such as an alert that guides the user to reduce pressure or distribute their brushing more effectively.

Subsequently, the mid- to late 2010's were marked by the introduction of Amabrush, Chiiz, Blizzident, and a variety of other full-mouth toothbrushes, often marketed as performing better in terms of speed and effectiveness. For more details on these brushes, see section 4.3.

Throughout this development, the medical dishonesty of Dr. Scott's initial invention continues to appear in one form or another: although most brushes have not been shown to be more effective than a capable manual brusher, electric brush manufacturers typically claim to offer superior performance.

Figure 09. Modern toothbrushes cater to specific subgroups (Oral-B, 2016).

Figure 10. Emmi-dent, a stationary ultra-sonic toothbrush shown to perform worse (Saruttichart et al., 2017) than an ordinary manual toothbrush (Emmi, 2017).

Overall, therefore, the development of electric toothbrushes has seen a progression from a medical assistance device, to a personal health product, to a combination of convenience and beauty product. Diversification of the market has introduced products which focus on particular markets, including children- and gender-specific brushes.

This diversification, especially of the high-end market, may prove to be relevant when choosing an aesthetic and promotional position for the product: focusing on the beauty market segment may alienate the health audience (to an extent), and vice-versa.

4.2. Stakeholder Analysis

Given the more complicated nature of the purchasing and production process of a custom mouthpiece compared to a standardised version, there are more stakeholders involved. Naturally this results in possible conflicts of interest.

4.2.1. End User

The end user of the mouthpiece itself is, by necessity, quite closely involved with the product from the start. As their dental data is required for the customisation to take place, their identity must be known even before the manufacturing can begin – a significant departure from the mass produced standard mouthpiece.

It is in the interest of the user that the scanning process is minimally intrusive and time-consuming, that the processing time is kept to a minimum, and that maintaining a working product consumes the smallest possible amount of effort.

4.2.2. Client

Compared to the standard mouthpiece, which was designed with the context of a separate B2B client and user in mind, this product is more likely to feature a single person in both roles. As the user must be involved in the purchasing process, non-user clients may be limited to edge cases.
Given this information, certain assumptions about the client can be made (though, of course, they should be validated). Someone who goes through some considerable up-front effort to obtain a custom mouthpiece is more likely to be personally invested in qualitative dental care. They may have a medical reason -- such as unusual dental anatomy -- for wanting a custom product. This possibility emphasises the importance of supporting possible irregularities, such as extreme dental arches or hypodontia (see chapter 05).

It is in the client's interests that the upfront design and manufacturing costs are kept to a minimum, that the organisation of the scanning and ordering process is as simple as possible, and that the product requires a low amount of work and investment.

4.2.3. Dentist

The dentist responsible for taking the 3D scan or cast is of paramount importance in the chain of purchase. Not only is their availability and willingness to cooperate with the program necessary for the product to be made in the first place, but consumers tend to rely heavily on advice and recommendations from their attending dentist.

The interests of the dentist are chiefly financial. Dental 3D scans are usually a billable service, although the cost of an individual scan--typically between 50 and 100 euros, depending on the country--may not be sufficient to justify the acquisition of the scanner in the first place. For that reason, allowing the 3D registration to happen at minimal cost (for instance, by using a cast instead of a direct scan) is of importance. In terms of maintenance support, the dentist may be useful in diagnosing any points of imperfect cleaning, and consequently recommending model updates or rebuilds.

Figure 11. The standard toothbrush was designed with a client/end user separation in mind.

The dentist obviously has a vested interest in the quality of any service they provide or recommend, meaning the performance of the mouthpiece (and, perhaps, more specifically the difference in performance when compared to other brushing tools) is an essential point of consideration to them.

As an aside, manufacturers of 3D scanning hardware and analysing software have struggled to find a receptive audience amongst dentists, since they do not yet often have a clearly defined purpose for the scans. Although this may complicate the production process initially, it does mean that the they might have an interest in mutually beneficial cooperation.

4.2.4. Dental Robotics

Dental Robotics have a number of minor interests besides the main objective of profitability. Being able to boast a more 'professional' mouthpiece may further the extent to which the mainstream mouthpiece is known, generating additional interest.

Customers who have already invested in the design of a custom mouthpiece may be more inclined to remain patrons of the company out of a vendor lock-in principle, which could provide a more reliable and consistent revenue stream for Dental Robotics.

Additionally, with the custom mouthpiece Dental Robotics may well be able to service a greater segment of the market compared to both their own mainstream mouthpiece, and to competing products.

4.2.5. Established competition

While there is no major direct competition to custom mouthpieces (see section 4.3.), important players in the field have been known to field extensive lawsuits in response to competition claiming increased performance. (Manatt, 2014). Similarly, high-profile acquisitions of relatively minor players are quite frequent (Neff, 2002). If Dental Robotics manages to capture a market segment which has hitherto been untapped--namely, custom toothbrushes--it may become more attractive for another large company to acquire it rather than to attempt legal recourse.

Taking these stakeholders into account, several required properties of the mouthpiece become apparent.

Primarily, the mouthpiece must be able to provide benefits beyond the standard mouthpiece which are apparent to the end user: after all, it cannot rely on being purchased by an external agent. Examples of such benefits might include improved comfort for non-standard dental arches, or sufficiently improved performance to warrant recommendation by dentists.

Additionally, a smooth trajectory from purchasing decision to delivery is paramount. Effectively integrating the scanning and purchasing process with regular dentist services could reduce the effort on the part of the user, as well as the perceived cost. Due to the low availability of 3D scanners in practices, this may have to include a scanning service which processes dental casts.

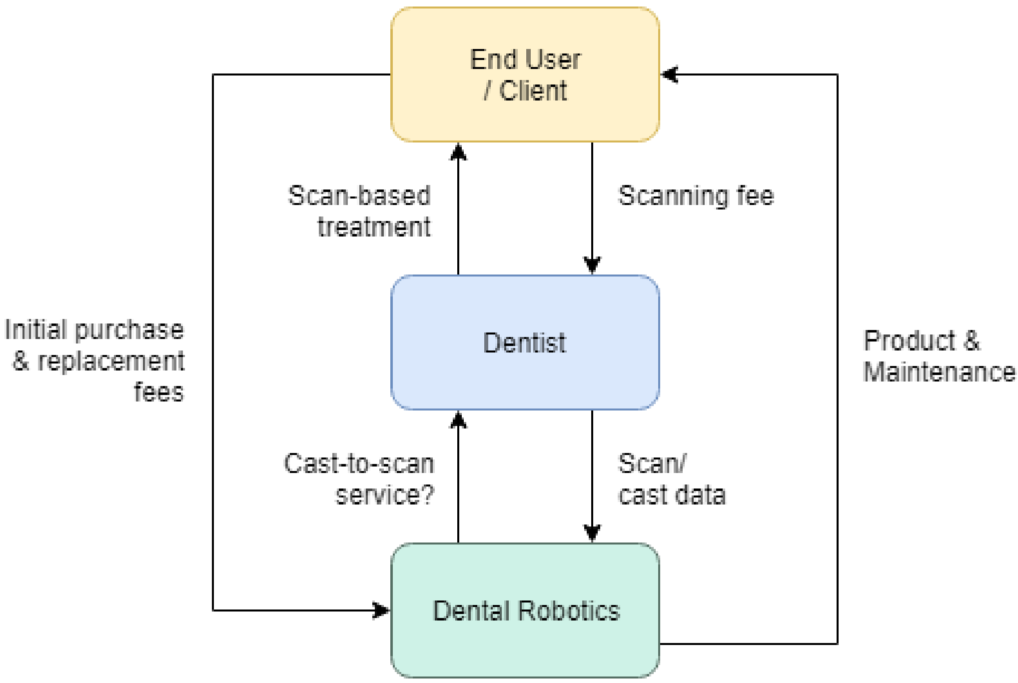


Figure 12. Overview of relations between end user, dentist, and manufacturer.

4.3. Competition

Recent years have seen a large number of advanced toothbrush models reach the market. Direct competition to a fully actuated custom mouthpiece is not yet available, but many of the constituent components of this design brief--customised mouthpieces, actuated mouthpieces, and general advanced toothbrushes--are being developed or already for sale. This section looks at the market position of a representative sample of such toothbrushes.

4.3.1. Customised mouthpieces

Fully customised toothbrushes have only recently become viable with the emergence of low-cost 3D printing. For this reason, only one major manufacturer exists in this field.

4.3.1.1. Blizzident

Probably the closest analogue to Dental Robotics' goal of a customised mouthpiece, Blizzident is a relatively new business which sells both brushing and flossing mouthpieces customised to the user's dentition. The mouthpiece is not actuated, instead relying on grinding motions from the user to clean the tooth surface (Blizzident, 2013).

The mouthpieces are described as 'tailored', relying on a 3D scan made either directly (which is estimated at 100 dollars) or from a stone cast (estimated at 50 dollars). The processing of the scan into a mouthpiece costs 150 dollars, and the individual mouthpieces are sold at a rate of 50 dollars a piece. Additional fees are charged for shipping (29 dollars) and accelerated production and shipping (up to 130 dollars).

Figure 13. Blizzident 3D Toothbrush (Blizzident, 2018).

These prices suggest that a large amount of manual work may be involved in making these brushes.

4.3.2. Actuated mouthpieces

Compared to customised mouthpieces, the market for automated mouthpieces is positively crowded. After a highly successful Kickstarter by Amabrush, several manufacturers have engaged with the principle through crowdfunding and other media.

4.3.2.1. Amabrush

Visually very similar to the mouthpieces used by Dental Robotics, the Amabrush consists of a flexible mouthpiece actuated through vibrations. Silicone bristles make contact with the user's teeth to reduce plaque build-up. Built-in channels are responsible for the distribution of toothpaste through the mouthphiece.

Figure 14. Amabrush Basic starter kit (Amabrush, 2018).

The mouthpiece is available in a single size – a size which, according to the website, 'is suitable for adults and teenagers over the age of 14' (Amabrush, N.D.).

Though not yet officially released at the time of writing, the straightforward nature and widespread popularity of the brush has attracted a variety of imitators. Tests of those imitations within Dental Robotics have not been encouraging--vibrations are not transferred to the teeth effectively, and the cleaning results are consequently highly mediocre.

The set, including actuator and charger, ranges in price from 130 to 200 dollars. Separately from the actuator, additional mouthpieces are sold at a price of 10 dollars (Amabrush, N.D.).

4.3.2.2. Chiiz
Chiiz, another crowdfunded manufacturing project, uses a comparable, but noticeably different-looking mouthpiece to Amabrush, actuated through sonic frequencies rather than a conventional vibration motor. Although sonic actuators have been implemented in conventional electric toothbrushes before, some critics have argued that its use in this case is only meant to circumvent copyright claims from Amabrush (Ekblad, 2018).

While brushing time is stated as 30 seconds, a relatively long time in the market segment, the actuator has been designed to be hands-free, intending for users to undertake other activities in the meantime. At an 80 dollar starting price, it tends towards the cheaper end of the market, though additional toothpaste mousses are sold at a considerable premium (Ekblad, 2018).

This product was designed with a large and small mouthpiece – a difference which manifests in the dental arch length rather than its shape or width (Chiiz, 2017). All starter kits contain both versions, most likely because there is no dental data available to make the choice beforehand.

4.3.3. Advanced toothbrushes
The high-end electric toothbrush market is currently still dominated by conventional electric toothbrushes, mainly in the hands of Philips and Oral-B. Due to the sheer number of models developed by both companies, this section instead discusses both manufacturers on a more general level.

4.3.3.1. Oral-B
Oral-B mostly dominates the mainstream electric toothbrush market, but also owns the Genius brand—a roughly $200 electric toothbrush presented more as a beauty product than a medical device. It pairs with a smartphone app which uses the front-facing camera to track brushing activity, checking the location of the brush and notifying the user when they need to switch sides.

Figure 16. Oral-B Genius 9000 (Oral-B, 2018).

4.3.3.2. Philips
Philips occupies much the same market spot as Oral-B, their Sonicare brand being sold at aroud $200. The brushes are sonically actuated and notably 'designed', with the traditional charging station integrated in a stylised charging glass. Like Oral-B, their devices can couple with a smartphone to check brushing time and pressure.

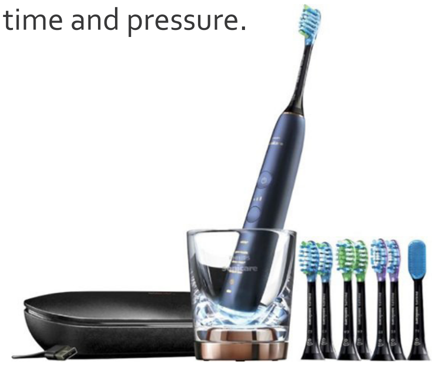


Figure 17. Philips Sonicare DiamondClean (Philips, 2018).

Figure 15. Chiiz: Toothbrush 4.0 (Chiiz, 2017).

4.3.3.3. Kolibree
A relatively minor player in the market, Kolibree were kickstarted in 2014 and have released several products since. Their toothbrushes combine sonic actuation with Bluetooth phone connectivity, tracking locations brushed, brushing frequency, and solving a myriad of problems with unspecified 'AI technology'. The $130 Kolibree Ara focusses heavily on parents, stressing that children's brushing techniques no longer need to be checked. The app includes a variety of games to encourage frequent brushing.

Figure 18. Kolibree connected toothbrush (Kolibree, 2015)

4.3.4. Conclusion
As already discussed in the section on the history of the electric toothbrush, these high-end toothbrushes are branded to represent more than just a personal care necessity. Depending on the specific target market, they may be sold as beauty products, efficiency aides, medical products, or even as a form of entertainment.

Given the nature of the product design brief, it makes sense to compare these products on the spectrum of personalisation. Figure 19 illustrates such a spectrum. The image indicates that while the market may seem relatively saturated at first glance, no products directly occupy the highly-personal segment at a low or even medium price.

When establishing the requirements of the mouthpiece, then, it is important to consider that the product must be presented as sufficiently distinct and custom, while retaining a manufacturing complexity that does not put it in the >$250 initial investment price range of the Blizzident.

Figure 19. Competing products plotted against quantitative interpretations of price and available market.

4.4. Market Context Conclusion

With the standard mouthpiece, Dental Robotics have taken up a clear position in the market: a B2B setup where clients are separate from the end users, and are mostly motivated by the time-saving properties of the Air One. The custom version requires an entirely different approach, and is therefore likely to present entirely different demands.

The appendix, section 4, covers a ballpark estimate of the expected sales volumes of the custom mouthpiece over the first few months of implementation, based on comparable projects from Oral-B and Amabrush. Going forward in this report, sales volumes will be assumed to be in the range of 10.000 units over a span of six months.

Compared to traditional toothbrushes, the custom Air One can be presented as a faster, more efficient alternative. To this end, the toothbrush should be able to guarantee cleaning that at least rivals typical manual brushing performance, while maintaining the speed improvement that the Air One promises.

Compared to more high-end electric toothbrushes, the custom mouthpiece offers a relatively sparse but overall more useful level of personalisation. By stressing this level of personalisation--both compared to traditional high-end brushes, and compared to the standard Air One--the custom mouthpiece can maintain its own distinct position in the market.

05. Dental Properties

The main purpose of the custom mouthpiece is to increase plaque removal around interdental and gum line regions. To accomodate this across a sufficient section of the population, the mouthpiece must support a range of dental arches as well as the most common dental pathologies. A dentition generator makes sure that STLs of unusual anatomies are available.

The design of the mouthpiece revolves entirely around the geometry and location of the teeth in the mouth. This chapter will discuss the nature of toothbrushing, the normal and pathological patterns of dentition, and how to convert these data into a more usable dataset.

5.1. Toothbrushing basics

The main purpose of toothbrushing is to remove plaque build-up from the teeth, an adhering film of microbiology which subsist on nutrients from the patient's diet. Their presence is associated with caries and tooth decay due to the acidic nature of their waste products, which acts as a solvent on the tooth's outer layer of enamel. An additional side effect of plaque is periodontal disease, including gingivitis and periodontitis: inflammation of the gums, which can lead to tooth loss in extreme cases (Ten Cate, 2006).

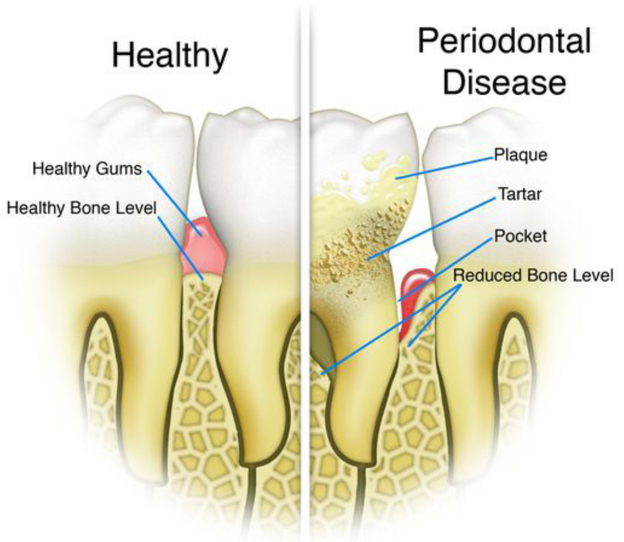


Figure 20. Periodontal disease derived from lacking dental hygiene (Moumneh, n.d.)

Plaque typically accumulates near the interdental regions and gums of the patient for a variety of reasons--brushes typically have more difficulty reaching those locations, regular tongue and skin contact is less likely, and regions with multiple surfaces often have better adhering properties.

While brushing is necessary, it can in itself have negative effects if executed imperfectly. High pressure during brushing may result in gingival recession, as well as sub-standard brushing results. Brushing for more than two minutes, or exerting a force of more than 1.5N, with a traditional toothbrush was found to have no beneficial effects to plaque removal (Haeseman, 2003). Rounded bristles typically display lower microscopic damage to the enamel than flat-cut bristles, while also resulting in lower gingival recession (Mulry et al., 1992).

Cleaning performance is highly dependent on the wear of the toothbrush, although age is not necessarily a reliable predictor for this wear. Typical recommendations are to replace the toothbrush once the bristles are visibly misaligned, or to use the wear indicators included in some more expensive toothbrushes.

5.1.1. Current mouthpiece performance

Currently, the Dental Robotics toothbrush is capable of cleaning relatively large percentages of plaque consistently. This may, however, not be sufficient: as the uncleaned plaque is often found in the pockets or near the gums, local plaque build-up could continue for relatively long periods of time without being disturbed (see figure 21).

In part, this result is due to the same reasons that plaque builds up around the pockets in the first place: like the patient's tongue and skin, the uniform nature of the pneumatic actuator means that it has difficulty accessing locations with relatively high local curvatures.

As plaque build-up is typically most harmful around interdental and gingival areas, it is therefore reasonable to state that the main objective of an improved mouthpiece would be to increase contact and plaque removal around these same areas.

Figure 21. Dental plaque residue: current performance versus target performance.

5.2. Dental Anatomy

Dental anatomy is a widely studied specialism as part of orthodontics, dentistry, and surgery. It also has fairly obvious implications for the range of geometries which the mouthpiece must be able to accommodate. This section will discuss dental anatomy mostly on the scale of the whole dentition, both in normal cases and in the case of common pathology.

The adult human mouth contains 32 teeth, including wisdom teeth. These are arranged, moving outward from the centre of either the maxilla or mandible (upper and lower jaw, respectively), as two incisors, one canine, two premolars, and three molars. The presence of the last molars, known as wisdom teeth, is inconsistent: because as many as 72% of people experience medical issues with their third molars, they are often moved prophylactically (Dodson & Susarla, 2010).

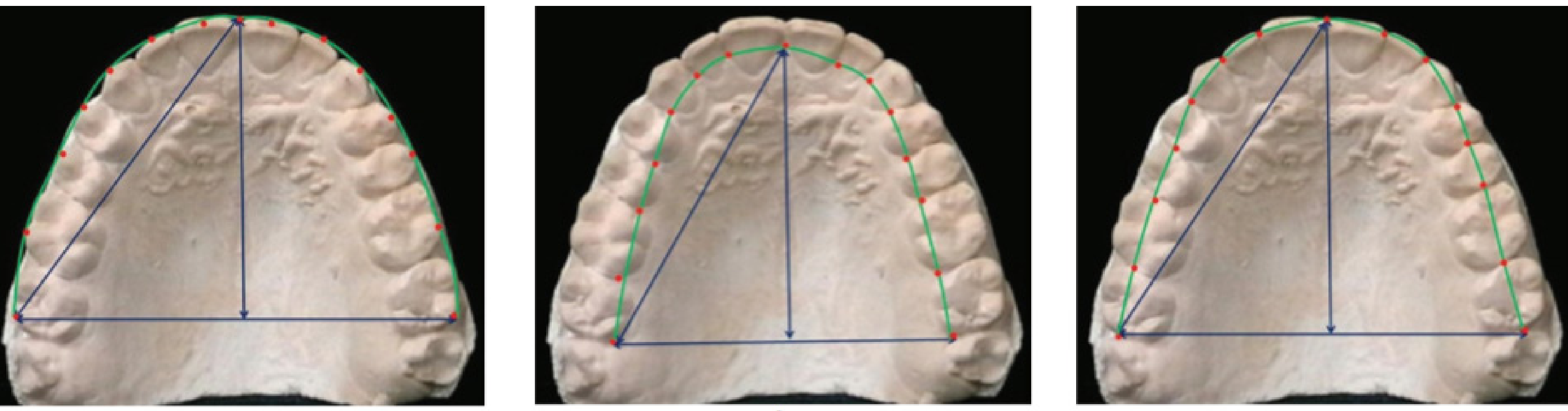
5.2.1. Dental Arch

Typically, the arrangement of teeth is described using the dental arch. This curve describes the way that mandibular (lower) and maxillary (upper) teeth are arranged on their respective jaws. Note that the arches do not describe the width or spacing of teeth along these arches.

Dental arches can be described using the outer boundaries of the teeth (dental arch), the inner boundaries (alveolal arch) or the mean between the two (dentoalveolal arch). The arch is commonly described using its total length, its height and width, with the ratio between the latter two being referred to as the 'Arch Index' (Dmitrienko et al. 2014).

An arch index (based on the dental arch) is considered mesognathic with a value of around 0.74, with values of 0.7 and 0.77 being the respective boundaries for brachygnathism and dolichognathism, each category covering roughly 1/3 of the population.

Figure 22. Possible dental arch derivations (Dmitrienko et al., 2014)



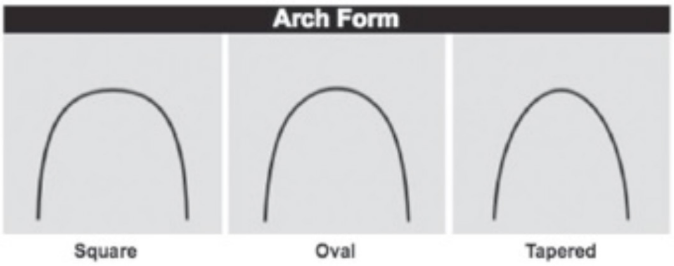


Figure 23. Exaggerated dental arch shapes (Paranhos, Trivino & Jólias, 2011)

Whether these dental arches are sufficient to accommodate the number of teeth of the individual depends on the width of the teeth: microdontia and macrodontia occur when the mean width of the molar crowns exceed the boundaries of around 10.6-11mm, respectively.

Arches are traditionally classified in one of three categories: Square, ovoid, and tapered. These categories are used by orthodontists to select wires for tooth realignment, and are distinguished by the relative frontal width of the arch.

5.2.1.1. Relationship between arches

The maxilla is typically suspended over the mandible. This relationship is described as the 'Gnathic Index', a ratio in arch depth in which anything up to 98 is considered retrognathic, 98-103 is considered mesognathic, and greater than 103 is considered prognathic (Ireland, 2010).

Attempts have been made to predict arch width from various tooth sizes, such as Pont's Analysis. The correlation between width and arch width, however, is weak, and does not transfer well between populations (Dalidjan et al., 1995).

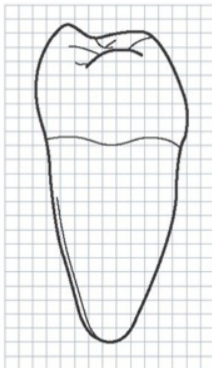
When dealing with 3D measurements, the cusps of individual teeth can be described as lying in a spherical range with around 1.7-1.9% deviation in healthy adolescents, taking into account a vertical variation that traditional dental arches do not (Ferrario et al., 1999). Unfortunately, the approach has never become a standard, and available data in this format are sparse.

5.2.2. Occlusion

Contact between the mandible and maxilla is defined as 'occlusion'. Orthodontistry typically deals with malocclusion, divided into classes II (in which the mandible is too far anterior) and III (in which the mandible is too far posterior) (Muhamad, 2014). These classes are roughly equal in size in most populations, causing predictions of one dental arch based on the other often to be inaccurate.

Other occlusion issues are caused by, for example, crowding (when the teeth are too close together compared to their tooth width). Bolton's ratio refers to the relative average sizes of teeth in the mandible and maxilla, and is therefore closely related to the occlusion of the individual (Wędrychowska-Szulc et al., 2009) and the relative overlap of the mandible and maxilla.
A patent has been granted to use 3D scans of patient dentition at two different stages to automatically detect changes, highlighting them and extrapolating future dental variance (Sandholm et al., 2015).

Figure 24. The cervical line on a mandibular second molar (WWH, N.D.)



5.2.3. Gum lines

Gum lines, the intersection between the tooth and the gums, are less well-defined than general dental anatomy, but typically vary within a small distance from the so-called 'cervical line'. This curve is defined as the border between the crown and the root of the tooth, usually visible as a ridge of high curvature on the tooth (WWH, N.D.).

Unlike most dental anatomy, which is typically consistent from the point of wisdom tooth eruption onwards, gum lines can be quite variable over time, responding as described in 5.1. to excessive brushing pressure, infections, and plaque. To keep track of both rapid and long-term changes, a patent has been granted to use 3D scans of patient dentition at two different stages to automatically detect changes, highlighting them and extrapolating future dental variance (Sandholm, Jouhikainen & Dillon, 2015).

5.2.4. Dental pathology

Most pathological dental conditions are sufficiently rare that taking them into account for the design space of the mouthpiece is unlikely to be feasible. Some notable exceptions to this rule include crowding and hypodontia, as well as tooth loss.

Crowding--that is, a comparatively large tooth size versus the jaw size--can lead to more unpredictable tooth positioning in the jaw., and may obstruct the reach and positioning of bristles in a mouthpiece. Crowding is associated with an increase in plaque-related afflictions for much the same reason (Lestrel et al., 2004).

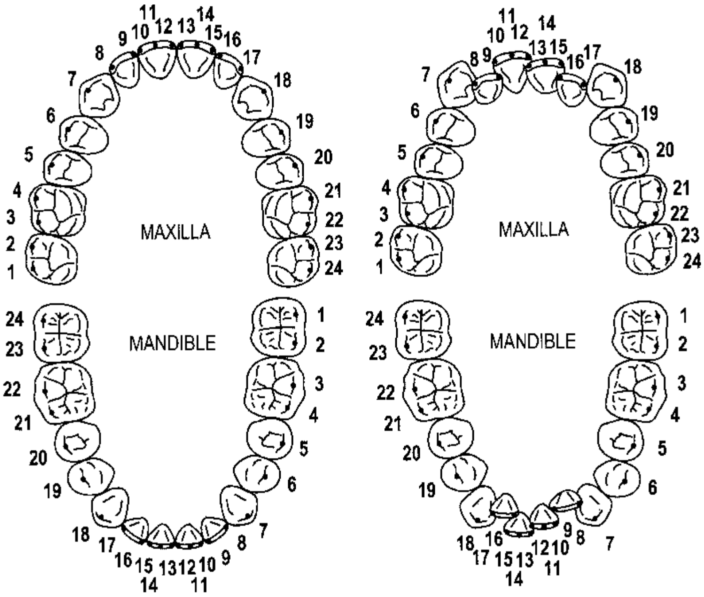


Figure 25. Normal alignment (left) versus extreme crowding (right) in a standard dental arch (Lestrel et al., 2004).

Hypodontia is perhaps the most common fundamental deviation from standard dentition, which occurs in as many as 8% of adults. Typically, this is in the form of an absent second molar or premolar. While not formally defined as a part of dental pathology or hypodontia, the absence of third molars is even more common. 20-23% of American adults are missing a wisdom tooth, while a large majority (about 70%) experience enough misallignment or crowding to warrant a wisdom tooth extraction (Chussid, N.D.).

Compared to a full set of teeth, hypodontia typically results in exposed tooth surfaces which are difficult for a mouthpiece to reach, as they are not parallel to the dental arch.

Loss of teeth has been reducing consistently over the past few years, but remains extremely common. Causes include accidental and violent damage, advanced caries and peridontitis, and surgical removal due to related issues. In 1996, only 30.5% of adult Americans retained all 28 non-wisdom teeth, although loss percentages drop sharply in younger populations (Marcus et al., 1996).

Figure 26. Extreme hypodontia (Puttalingaiah et al., 2014).

This kind of tooth loss typically occurs in the case of molars and premolars, which often receive the smallest amount of dental care compared to the incisors and canines.

Considering the array of possible variations and defects of human dentitions, the number of parameters to be taken into account is virtually endless. Section 5.3. will demonstrate a way of making these data more visible. That being said, the main factors to be taken into account when designing a data processing pipeline include the width, depth, and general shape of the dental arch, the effects of crowding and vertical displacement on the position of individual teeth, the height and shape of the gingival line, and the possibility of tooth gaps and absent molars. It must also be possible to account for considerable misalignment of the mandible and maxilla.

5.3. Dental Reconstruction

The number of variables that determine the position, angle, and size of the individual teeth is enormous. The following section describes the implementation of a 'Dentition Generator', which uses a number of data (especially data which are commonly gathered during dental medical research) to estimate the dentition that gave rise to the data, allowing for simulation of scan data of larger populations than Dental Robotics have access to.

Note that the anatomies generated by this tool are always approximations, as details are inevitably lost during the measuring process. As such, any high-value validation should always be performed on a representative set of real-life data once available.

5.3.1. Dental Arch

Typically, dental research records four measurements of the dental arch: the anterior width (length of a line between the canines), anterior length (length of a line between the aforementioned line and the central incisors), and the posterior length and width (based on the line between the second molars). By extending these measurements from a central point for the central incisors, assuming symmetric proportions, one ends up with five points on the dental arch.

5.3.1.1. Dental Arch types

While the recorded points of the dental arch can be implemented easily, blindly interpolating between these points is misleading. Introducing traditional dental arch types can help to minimise this issue.

Arch types are often classified inconsistently - many orthodontic suppliers use their own subdivision. The arches used in this model have been taken from the 3M Oral Care Orthodontic Product Catalog 2017, but could easily be replaced by any preferred set.

The algorithm incrementally scales all three curves to optimally fit the points generated by the data. A curve is selected either manually or using least-square point fitting. The curve is then trimmed to fit the length of the arch, and subdivided into straight segments representing the respective width of individual teeth.

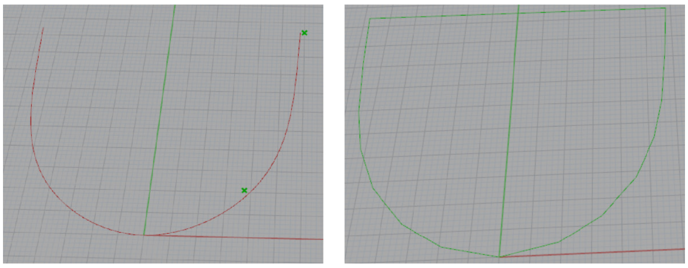
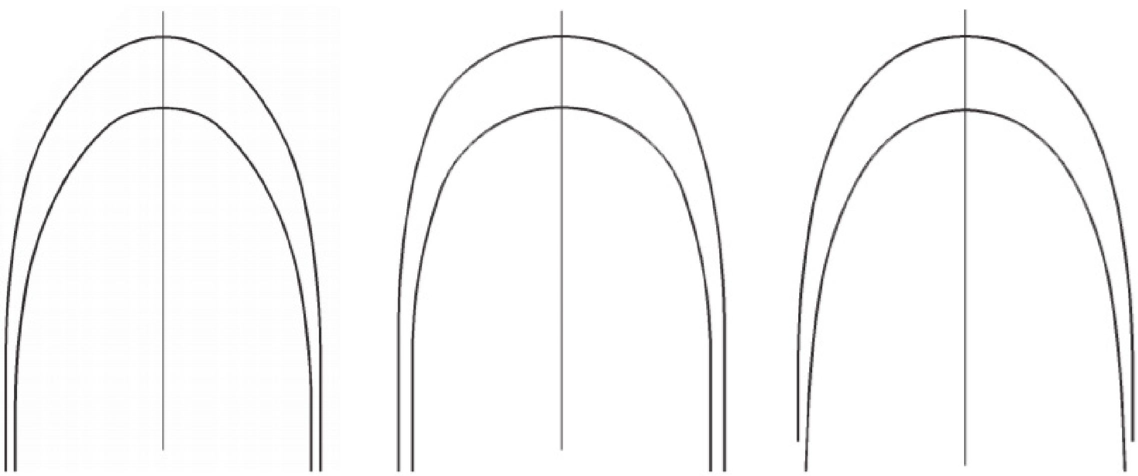


Figure 28. Arch fitting and segmentation.

5.3.1.2. Tooth geometry

Individual tooth geometry is typically not available from measured data, except for the width of the teeth. As such, the generator uses a set of publicly available tooth STLs (Stokes, 2017), aligned with the denture using reference planes matched with the base STL.

Figure 27. Dental arch guidelines used as orthodontic guidelines (3M, 2017).



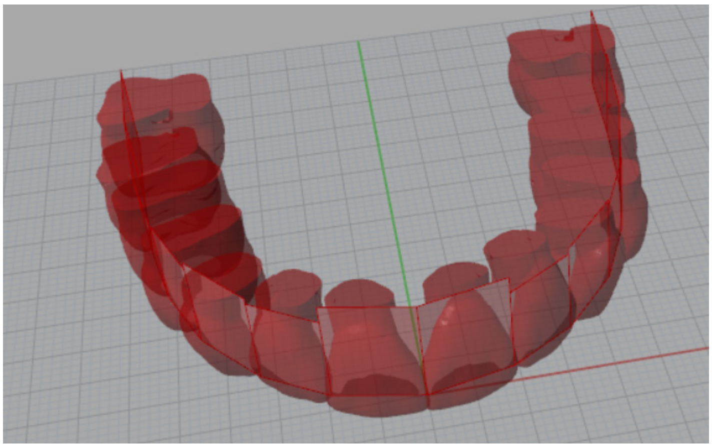


Figure 29. Tooth STLs fitting to guiding planes.

Sliders can then be used to create additional patterning, including wave-like displacement (to raise, lower, or rotate the molars or incisors) and semi-randomised displacement (like individual twisted or undersized teeth). Unlike the other parameters, these patterns do not correspond with real-life data, as similar deviations are typically not recorded in mass data.

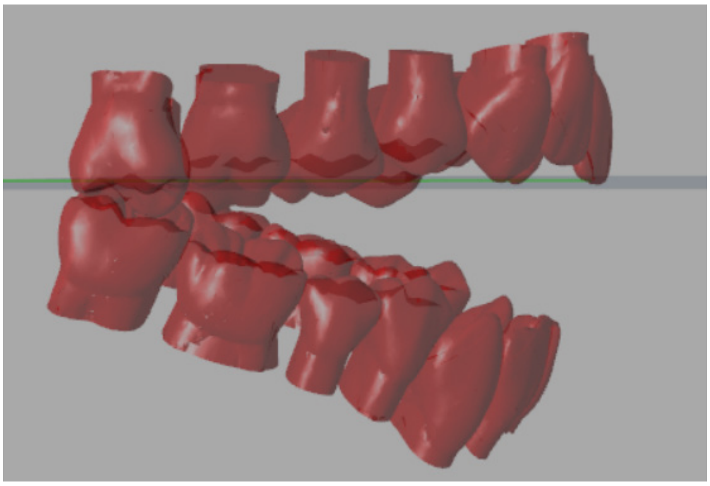


Figure 30. Randomised height and angle variation.

5.3.1.3. Gums

Using approximate data from WWH (N.D.), it is possible to estimate the cervical line--and, thereby, the average gum line--by intersection the projected lines with the tooth STL. These gum lines can then be varied randomly in much the same way as the other variables, though data on its normal distribution are not available.

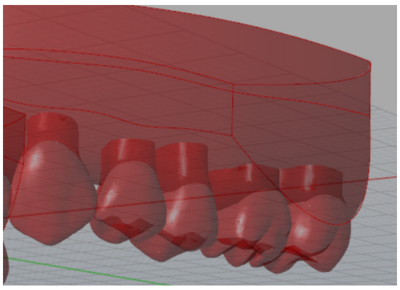


Figure 31. Gum mesh through cervical lines.

5.3.1.4. Validation

Although the algorithm cannot perfectly imitate existing casts, STLs of real-life casts can be used to validate the imitable properties of individual dentitions. The performance of the algorithm is defined here as the average distance between the generated geometry and the scan which the measurements were based on.

Figure 32 illustrates the performance of the algorithm without least-square fitting of the dental arch, by superimposing the generated geometry over the scan:

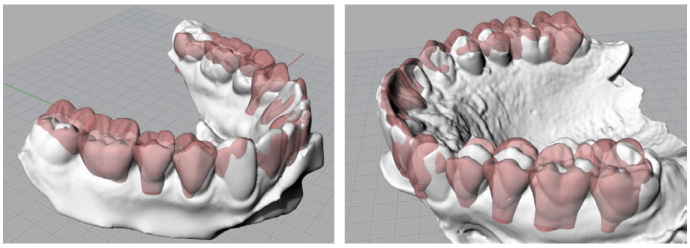


Figure 32. Standard arch accuracy overlay for a pair of example arches

While interdental regions match up to their original counterpart, usually to within one or two millimetres, the simulation fails on two parts: the height and angle of the teeth, and the arch between the canines and second molars. Introducing least-square arch matching results in the following overlap:

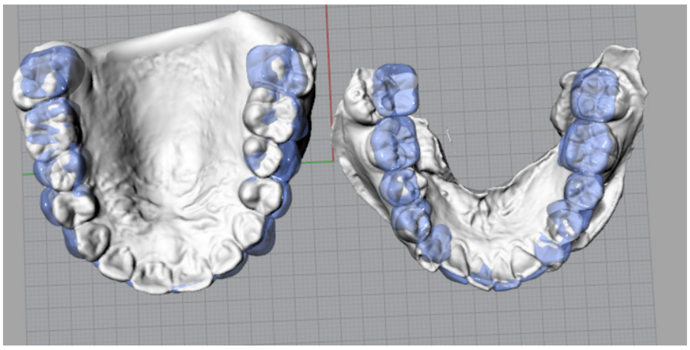


Figure 33. Least-square arch accuracy overlay on the same dental arches.

Validating the mesh overlap using the Hausdorff Distance filter in MeshLab results in a mean distance between the generated model and the nearest mesh vertex of 1.113mm--reasonably close for estimation purposes, but probably not within the required manufacturing tolerances. The second molars can deviate up to 6mm at one point. This makes the models useful for simulating unavailable dental deviations, but not for final manufacturing decisions.

06. Actuation

The standard mouthpiece is least effective at cleaning dental geometry with high local curvature. Motion-restricting geometry is found near the edges of the mouthpiece, and in convex areas. Fibers, thickness variations, sequential chambers, and segmentation can be used to fine-tune actuator behaviour. Manufacturing principles include casting, localised adhesive, foam milling, and experimental FDM methods.

This section covers mechanical principles used to actuate the standard mouthpiece, and the resulting advantages and limitations. It also covers various possible actuation principles and manufacturing principles for soft robotic applications.

6.1. Standard Mouthpiece

The standard mouthpiece currently in development by Dental Robotics consists of a single injection-moulded actuation chamber with a constant thickness, overmoulded on the sides to a rigid outer frame. Inflation results in the flexible wall expanding blindly outward until resisted by an external force, such as a tooth. Given ideal flexibility, this would result in the flexible shell forming perfectly around the shape of the teeth. In reality, the conforming nature of the shell is limited by material properties.

The extension of the flexible material is hampered by a number of factors:

- Closest to the rigid frame, the material is restricted in its freedom of movement

- Near the ends of the mouthpiece, the material curves sharply and is bonded to the central frame, again inhibiting movement

- While the 'lingual' (rear) surface is concave, the 'facial' (front) surface is convex, leading the lingual surface to extend more under a given pressure than the facial surface

- Once the mouthpiece makes contact with the outer surfaces of the teeth, material and pressure limitations prevent the remaining 'free' material from fully conforming to the interdental regions and pockets.

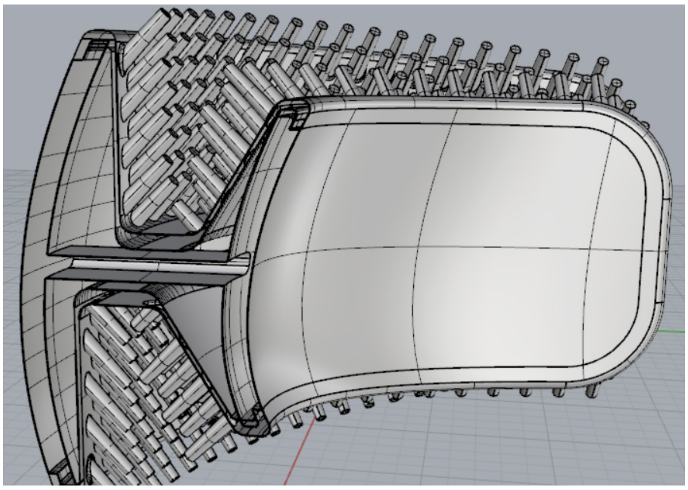


Figure 34. Cross-sectional overview of the standard mouthpiece.

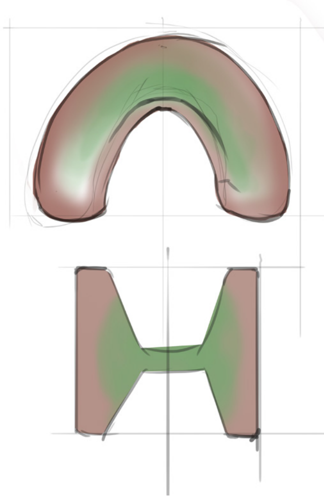


Figure 35. Illustration of the flexibility of the mouthpiece surface, dependent on surface orientation and distance from the frame.

6.1.1. Air regulation

The mouthpiece is actuated by regularly powering and relaxing a mechanical air pump in the handle. This causes the TPE to inflate and deflate regularly over a period of ten seconds, thus making repeated contact with the user's teeth. While parameters are still under revision as the product is being developed, inflation is currently toggled at a frequency of around 1 Hz, leading to an expansion of several millimeters throughout most of the mouthpiece. Pressure and exact deformation depend on the rigidity of the TPE membrane.

6.1.2. Finite Element Analysis

Finite Element Analysis, as executed by the company using Dassault Systems' Abaqus software, illustrates the measure of expansion of the mouthpiece under air pressure.

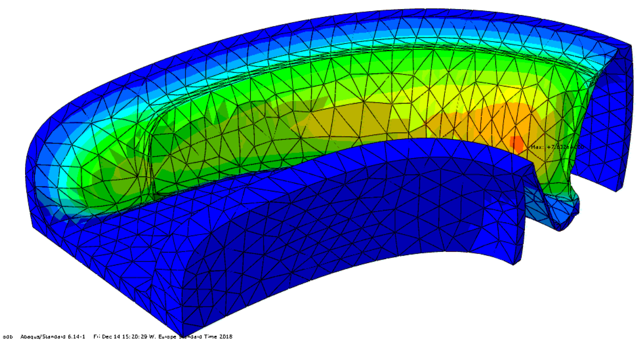


Figure 36. FEA expansion illustration.

While contact with the tooth surfaces has not yet been implemented in the simulation, it is immediately visible that the expansion of the material is strongly dictated by the flexibility and geometry of the material in its immediate vicinity.

Note that this type of FEA for hyperflexible systems is extremely time-intensive, and that consequently applying it for this project is not feasible within the given timeframe. That being said, future iterations of this project could profit from effective application of similar technology.

6.1.3. Contact results

As already discussed in an earlier section of the report, this actuation principle results in a number of imperfections in the cleaning results. Figure 37 illustrates that the mouthpiece currently performs well at removing plaque from the frontal tooth faces, but fails to properly contact the interdental regions and the pockets.

Figure 37. Plaque residue after cleaning.

These observations match up perfectly with the expected behaviour of a semi-flexible membrane under pressure, and with the behaviour shown in the FEA: The sheet mostly deforms over large surfaces, and maximum deformation is shown near the middle of these areas. Local high curvatures are much more difficult.

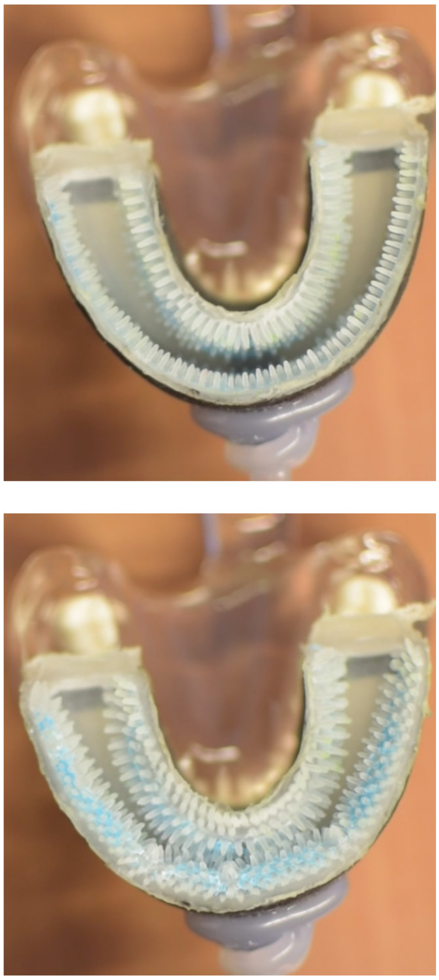


Figure 38. Single membrane actuation as used in the standard mouthpiece.

6.2. Pneumatic Actuation Principles

Generally, Soft Robotic Actuation relies on a geometry with varying levels of flexibility, causing it to extend or contract in the desired direction when inflated with fluids. Although a relatively young research field, a sizeable variety of actuation mechanisms have already been developed. Note that this list is not exhaustive, and only covers some actuators which could be relevant for the subject at hand.

6.2.1. Single membrane actuators

The most fundamental pneumatic actuation block is a flexible membrane which is put under pressure on a single side to expand outwards. This is both the working principle of traditional balloons, and of the current mouthpiece. The only means to control actuation is to vary in wall thickness, material flexibility, and geometry, which can influence the extent of the expansion.

6.2.2. PneuNets

The PneuNet could well be considered the most well-known soft actuation principle. Short for Pneumatic Network, the actuator consists of a sequence of elastic chambers forced to expand mainly in one direction during inflation. As the sequence expands, the device bends around a less flexible section of the actuator (Mosadegh et al., 2013).

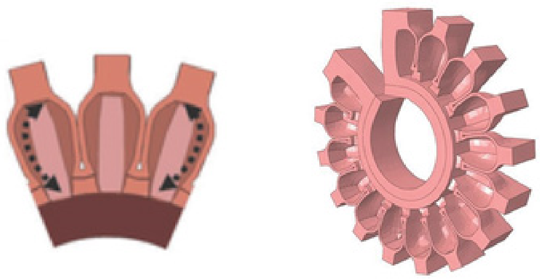


Figure 39. Pneunet actuation principle (SRT, N.D.)

Applying this actuation, which is usually implemented in a linear actuator, directly to the mouthpiece, is difficult: there is no one single direction in which the mouthpiece must be moved. The principle can, however, be used to force local expansion in particular regions of the system.

6.2.3. Fibre-reinforced actuators

A pneumatic chamber which has had at least one degree of freedom restricted by the introduction of non-flexible fibres in one direction, forcing it to expand instead in the remaining direction (Galloway et al., 2013). This could be implemented in a multidirectional surface to restrict motion along a particular path.

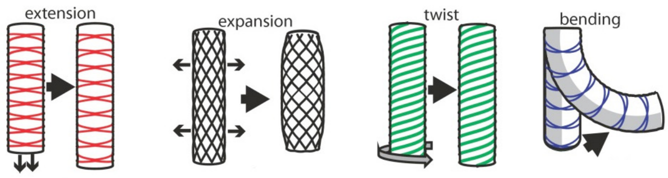


Figure 40. Fiber-reinforced actuation principles (Connoly et al., 2017)

6.2.4. Segmented actuators

Actuators can be sequentially connected to trigger one after the other, only inflating when the previous bellows have reached a minimum threshold (Overvelde et al., 2015). Such segmentation could be used to force the mouthpiece to more fully inflate and reach the desired geometry.

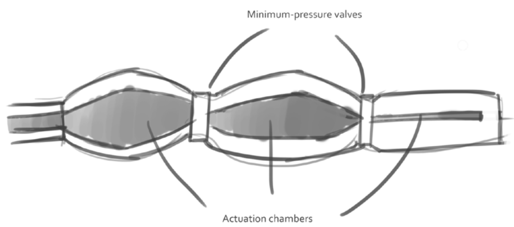


Figure 41. Sequential air chamber actuation principle.

During the early stages of the standard mouthpiece development, most of these pneumatic actuation principles were explored. Although they could often provide some measure of improvement to the actuation principle, their manufacture was typically too complicated to be implemented into a mass manufactured mouthpiece.

Implementing more advanced chambre or fibre techniques, however, may become possible once custom manufacturing techniques are introduced. In this case, the pneunet principle could be manipulated to create a bending motion, while fibrous additions might restrict the range of motion along undesired paths.

6.3. Manufacturing methods

Large scale manufacturing of pneumatic actuators is currently an unsolved problem, and one of the main reasons that soft robotics has yet to break through beyond research applications. That being said, several innovations have made the production of pneumatic actuators more viable, perhaps particularly so with regards to implementation for custom manufacturing.

6.3.1. Standard manufacturing

Most commonly, soft actuators are made by casting a flexible material (usually silicone) into a mould, and assembling the resulting shell parts into an air-tight product through adhesives. This manufacturing method, while effective in small batches, is expensive, unreliable, and inconsistent. Adhesive application is notoriously difficult to scale up, and frequently results in seal failures.

Figure 42. Simple adhered soft robot (Wu, 2018)

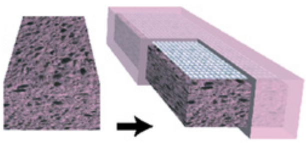
6.3.2. Grid silicone adhesion

Networks of small, pneumatically actuated chambers can be made using two layers of silicone, fastened together along grids to create isolated pockets (Sonar & Paik, 2016). This obviously grants far less productive freedom than cast-based manufacturing, but could be produced cheaply and reliably.

6.3.3. Foam-based manufacturing

Open-celled elastomeric foams can be used instead of a cavity to support complex shapes (Mac Murray et al., 2015). This can allow thermoforming around a core shape, reducing assembly complexity, but not necessarily solving the difficulties of airproofing the actuator.

Figure 43. Foam-based manufacturing: silicone is moulded around a open-celled foam. (Mac Murray et al., 2015)



6.3.4. FDM manufacturing

Experimental direct-print soft pneumatic actuators have been developed, using customised FDM printers to deposit both flexible material and reinforcing fibers directly (Byrne et al., 2018). Compared to SLS or SLA manufacture, this provides far greater design freedom and lower costs. The advantages in terms of assembly complexity are obvious, though adhesion between materials is still a problem. Mechanical linking may provide a solution in this case, although whether this result in reliably airtight connections is another question.

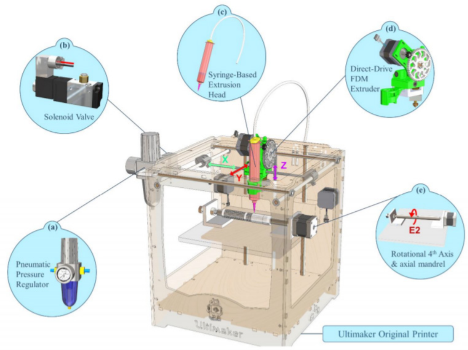


Figure 44. FDM manufacturing of cylindrical pneumatic actuators. (Byrne et al., 2018)

6.3.5. Standard mouthpiece manufacturing

The standard mouthpiece is created with more traditional manufacturing technologies. The TPE bristled layer is injection moulded in a milled mould. The outer parts of this mould are removed, inner segments containing the bristles are kept in place.

The frame is injection moulded in one piece and removed completely, and the two components are pressed together. An overmould of rigid material is then used to fuse the two components into an airtight finished product.

All of the aforementioned technologies can be made to include cast TPE bristles, as a part of the actuator itself. Nylon bristling, however, can only be applied to a pre-formed (flat) surface.

Although manufacturing of soft robotics is never exactly simple, technologies have been developed to cover a relatively wide range of production scales and complexities. Many of the aforementioned manufacturing technologies are applied in some shape or form in the concepts described from chapter 7 onwards.

07. Requirements

The main requirements and preferences of the project brief are outlined, based on the previous research. Demands include restrictions on interdental performance, population coverage, and manufacturability. Price requirements are based on the competitor prices established in previous chapters, making relatively low-priced manufacturing essential.

Based on the previous research, as well as details from the design brief, it is now possible to generate a list of specific, verifiable requirements and more general preferences.

Table 03 shows an outline of the main requirements, more of which are specified in the appendix, section 07.

As the scan should ideally remain relevant for a relatively long period of time to reduce the costs of repeated changes to the mouthpiece, the main target audience is likely not to have extreme dental issues. For this reason, the Functional section covers only relatively common dental afflictions, including hypodontia, crowding, misalignment, and wisdom tooth anomalies.

Safety measures are mostly focused around the basic requirements of FDA and CE approval in their most general interpretations. Antimicrobiality is not considered an inherent part of safety compliance, as they are more relevant to user comfort and aesthetics than user safety.

Quality restrictions cover both the level of detail required to sufficiently remove interdental plaque, and the preferred mode of failure: considering that the product works with pressurised air, it is important to be able to guarantee that any failure will occur without harmful consequences.

Manufacturing speed is of course relevant, but not particularly critical compared to many other products. Purchase already involves a dentist appointment--a waiting time is unlikely to be a decisive hindrance by comparison.

The price range has been established based on the desired market position of the custom Air One as established in the chapter on competition. That being said, depending on manufacturing technology, the acceptable price level can still vary wildly over the continuation of the project. Different levels of price could result in a dramatically different range of viable market segment.

Aesthetically, the range of possibilities is of course rather limited: the geometry may change from item to item, and material choices are relatively restricted for custom manufacturing. That being said, there are obvious demands to be made on the aesthetic level related to scent, flavour, texture, and comfort.

Requirements	Preferences
Functional	
The product covers at least P3-97 of adult arch dimensions	The mouthpiece should be capable of dealing with small changes in gum line and interdental location.
The product is demonstrably more effective in cleaning at least 30% of anatomies than the standard model	The mouthpieces should clean the largest amount of plaque possible, with a focus on the plaque in high-curvature regions
The product is capable of cleaning teeth regardless of non-pathological wisdom tooth eruption	Maintenance difficulty should be kept to a minimum
The product is capable of effectively cleaning teeth in the case of minor hypodontia	
The product cleans plaque from interdental regions and gum lines more effectively than the standard mouthpiece used on the same set of teeth	
The product supports nylon bristle tufts	
Safety	
The product exercises force that is within acceptable safety ranges for (sensitive) gums	
Materials and surface characteristics are safe for oral use	
Quality	
Under normal use, the product remains airtight within six months of purchase	Product lifespan should be extended as far as possible
Custom features correspond to the user's teeth to within 1mm tolerance	The main failure mode of the product should be non-catastrophic.
Manufacturing	
Given the dental data, manufacturing of the first mouthpiece can be done within one work week	The time between scan and delivery should be kept to a minimum
Time from scan to delivery is no more than three weeks	Manufacturing and assembly should be minimally complex
Timing	
The product can be put into serial production within one year of the graduation date	The production technology should require minimal research and development before implementation
Economic	
Upfront investments for the customer are no more than 150 euros, including the 3D scan	The variable costs of the mouthpiece should be minimised
Replacement mouthpieces are obtainable for less than 25 euros	
Mouthpieces retain 90% effectiveness in plaque surface removal for at least 3 months.	
Aesthetic	
The product does not present an intense or unpleasant taste, scent, or texture	

Table 03. General requirements and preferences for mouthpiece performance.

08. 1st Stage Synthesis

Rapid ideation and synthesis results in four different actuation/ manufacturing combinations, which are tested using basic principle prototypes. The resulting performance evaluation describes the relative viability of FDM pneumatics fabrication, mesh adhesives, multilayer actuators, and bristle milling on a basic level.

Having established the set of goals in chapter 7, the next step is to synthesise a set of ideas to work from. In total, this process spans three iterations (described in chapters 8 through 10). Each iteration contains a stage of divergence, prototyping, and selection of concepts.

For the first iteration stage, it is useful to consider a pair of requirements which are essential to the product: it needs to be producable in the near future, and it needs to be more effective than the current mouthpiece. This first requirement means that the production method must be an intrinsic part of the design. The second requirement means that this manufacturing must lead to a design which reaches the dental pockets and gumlines more effectively for a given individual--after all, this is where the existing mouthpiece currently fails.

8.1. Divergence

The first divergence stage centres around two basic components: actuation and manufacturing. Actuation includes different ways in which the pneumatic actuator can be influenced to interact more effectively with a given set of teeth. Manufacturing covers methods which can be applied to the geometric and functional constraints of the mouthpiece. For a full illustration of this ideation stage, see the appendix, section 08.

Subsequently condensing and cross-referencing those ideas in a morphological chart results in the overview of theoretically manufacturable principles which can be seen in figure 40.

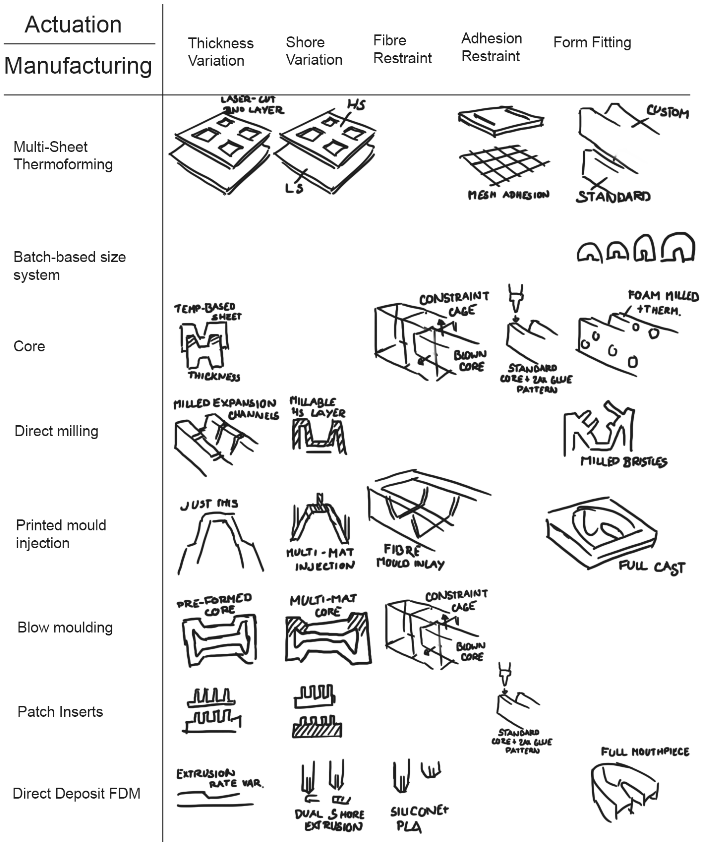


Figure 45. Cross-reference of actuation and manufacturing princples

By assigning these concepts a score on various criteria, and taking the weighted total of these scores, the most viable concepts can be condensed.

Criterion	Priority Weight
Complexity	10
Novelty	5
Geometric freedom	7
Arch range coverage	7
Potential resolution	8

Table 04. Criterion weight for evaluation properties.

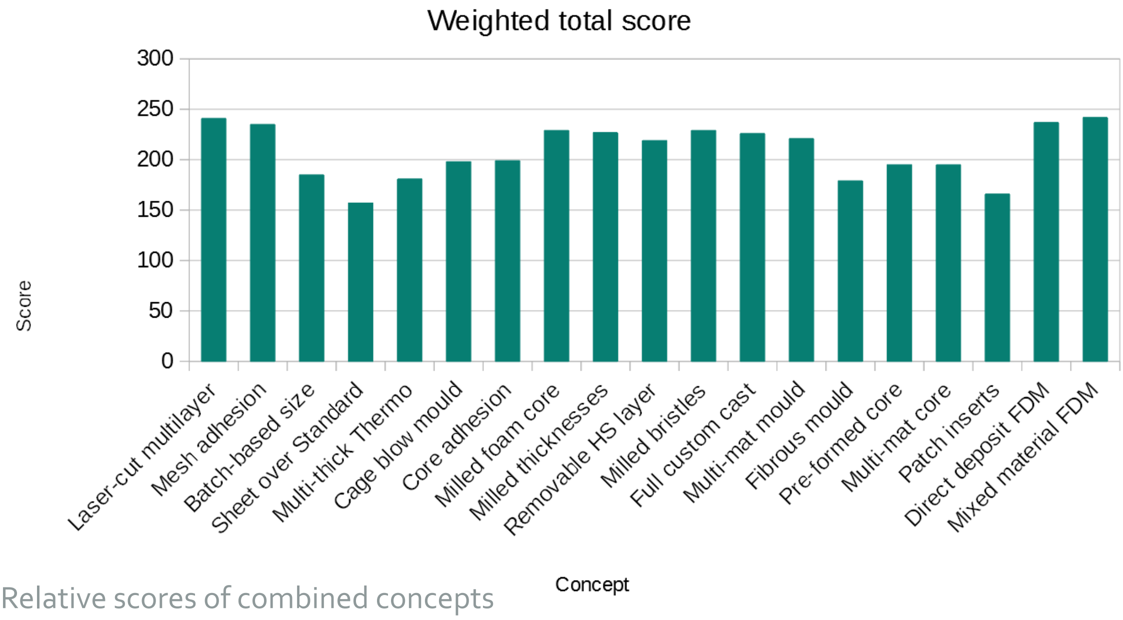


Figure 46. Relative scores of combined concepts

Based on this evaluation, the most promising directions are the following:

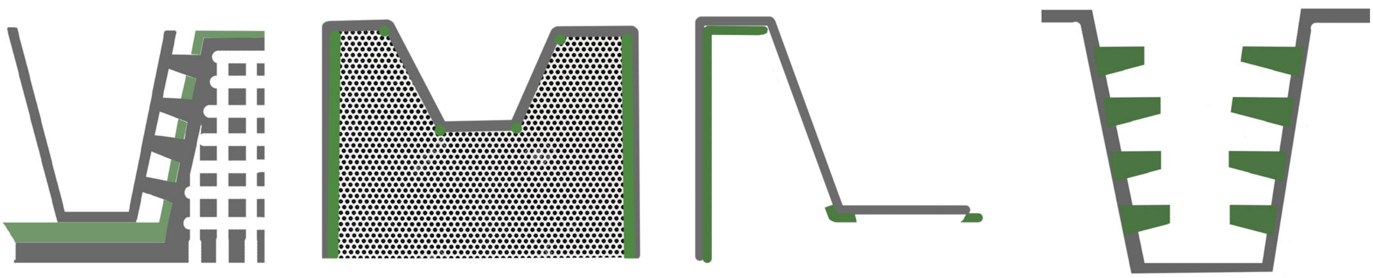
8.1.1. Mixed material FDM
A 3-axis FDM printer directly deposits rapid-cure two-component silicone over an elastomeric framework, according to the principle demonstrated by Byrne et al. (2018). Highly dependent on the ability to produce effective bristles.

8.1.2. Selective mesh core adhesion
A finely meshed core, made from either a 3D-printed material or an open-celled foam, is selectively adhered to an elastomeric outer layer. Locations with adhesion limit expansion, allowing the motion of the product to be customised. Dependent on the ability to manufacture an appropriately detailed mesh and clamshell.

8.1.3. Laser cut multilayer
A highly flexible, bristled outer layer is adhered to a selectively laser cut, rigid inner layer. Much like the mesh core, this inner layer restricts the motion of the mouthpiece, enabling some regions to expand more effectively than others.

8.1.4. Direct-milled bristles
Bristles of a pre-fabricated mouthpiece are milled to conform exactly to the dental curvature of the patient, necessitating lower expansion rates than the standard mouthpiece. Requires sufficiently stiff bristles to be trimmed without support, and may involve multiple base models to accommodate a large enough range of arches.

Figure 47. Concept illustrations: FDM, mesh adhesion, laser cutting, and direct milling, respectively



Freedom	Arch	Bristle	Actuation	Height
Mixed mat. FDM	1	1	1	1
Sel. mesh core ad.	2	3	3	3
Laser c. multilayer	4	4	2	2
Dir-milled bristles	3	2	4	4

Table 05. Ranked evaluation of freedom across important aspects of the mouthpiece.

8.2. Prototyping

In order to be able to make a reasoned decision between these fabrication methods, it is necessary to make some rapid prototypes of the basic working principles. This section covers some of the major possible obstacles for every manufacturing technology, a basic prototyping method to explore those obstacles, and a comparison of the results.

8.2.1. Direct Deposit FDM

While FDM printing would allow for virtually unlimited freedom in all of the parameters of the mouthpiece--including arch width, gum height, bristle length, and actuation--the technology is also likely to run into serious issues.

- FDM printed surfaces generally do not conform to food safety standards. For the product to be safe to use, an effective means of 'sealing' or evening the surface must be possible.

- Unlike TPE, the silicone used in FDM SPA (Soft Pneumatic Actuator) manufacturing does not adhere easily to non-silicone surfaces. The printer therefore needs to be able to create anchoring geometry, or some other additional means of connecting the 'rigid' and flexible materials.

- The nylon bristles will need to be attached directly, and exclusively, to the flexible membrane. For this to happen, the printer needs to be capable of extruding at least minor amounts of rigid material on a flexible surface, while insuring a solid and air-tight connection, all at relatively high bristle density.

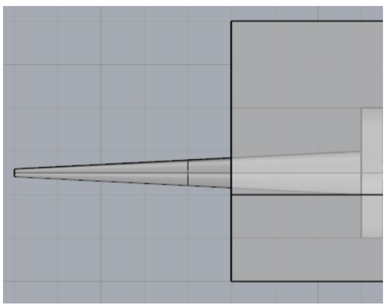


Figure 48. Nylon bristle between silicone layers

Testing this solution fully requires custom G-code as well as machinery, and is therefore not viable in the short term. Instead, the principles of bristle extrusion and anchoring can be tested by placing a flat layer of silicone on an FDM print bed, homing the printer onto the material, and extruding from there. By then manually depositing a second layer of silicone onto the bristles, the anchoring principle can be tested as well as the bristle extrusion principle.

Figure 49. FDM bristles between silicone layers.

8.2.1.1. Evaluation

Even a cheap FDM printer is easily capable of printing sufficiently large bristle extrusions at normal print speeds, without noticeable sag in the bridging. Although adhesion to the silicone is not an issue during the printing itself--after all, the bristles are still connected to the sacrificial wall--the resulting silicone-bristle-silicone structure does not adhere sufficiently to prevent loss of contact as the silicone flexes during use.

8.2.2. Selective mesh adhesion

Selective mesh adhesion would result in full control over arch geometry, but limited control over SPA actuation and bristle geometry. The following uncertainties may manifest as limiting factors:

- As the bristles have a constant length, the mouthpiece derives its performance from customised geometry and actuation. This means that it needs to be able to bulge sufficiently at least every few millimetres to reach the pockets and gum lines.

- The behaviour at the mesh adhesion points determines how detailed the adhesion pattern can be: if it fully prevents expansion, adhesion can only be applied to non-contact areas, restricting the possible arrangements compared to a more flexible adhesion.

- The mesh may result in a reduced airflow at high densities, reducing the mouthpiece effectiveness. On the other hand, a lower-density mesh may support insufficient surface detail to enable proper actuation.

As an efficient way of printing flexible meshes is not readily available, testing the adhesive behaviour and resolution of this manufacturing method can be done using an open-celled polyurethane foam, trimmed into a simple cylindrical shape and adhered selectively to a constant TPE outer layer. This allows the level of detail in the actuation, relative to the overall motion, to be compared with that of the Multilayer manufacturing method (see section 8.2.3.)

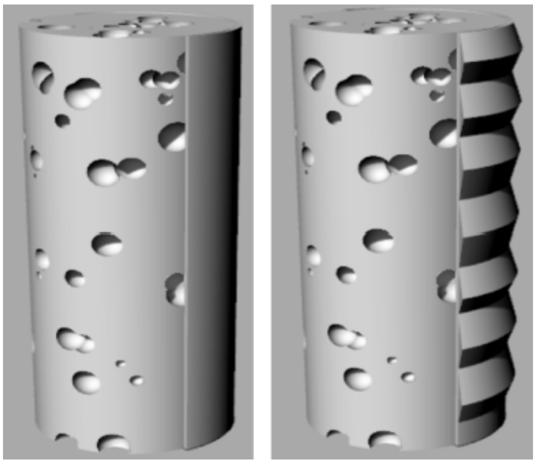


Figure 50. Intended expansion pattern of TPE sheet

3.2.2.1. Evaluation

When tested in this setup, the second afore-mentioned point appears to be the major determining factor: when adhesive is not applied, the skin inflates as normal through the foam. Once adhesive is patterned between the foam and the skin, inflation appears to be nigh on undetectable. Repeating the test with a reduced skin thickness, and a reduction in adhesion points, results in only a slight increase in actuation.

8.2.3. Laser Cut Multilayer

The multilayer system would enable flexibility in terms of actuation and arch size, provided the following restrictions are overcome:

- As the bristles have a constant length, the mouthpiece derives its performance from customised geometry and actuation. This means that it needs to be able to bulge sufficiently at least every few millimetres to reach the pockets and gum lines.

- The relative expansion of the local maxima (where the sheet is thinnest) needs to be sufficiently large compared to the overall tendency of the actuator.

Using the same basic setup from 8.2.2., it is possible to compare the performance of the multilayer system to the mesh-based approach: instead of using a mesh to restrict motion, a secondary, separately cast inner layer provides resistance.

8.2.3.1. Evaluation

Compared to the test described in 3.2.2.1., the effect of the additional skin appears reversed. Whereas the mesh constrains the skin to the point of non-actuation, the secondary skin provides very little resistance. The overall motion of the cylinder is constrained, in that the total bulge of the actuator is reduced, but the patterning of the individual sections does not manifest significantly.

Figure 51. From bottom left to upper right: Dual layer .8mm, mesh + .8mm, mesh + .4mm, and dual layer .4mm TPE tests

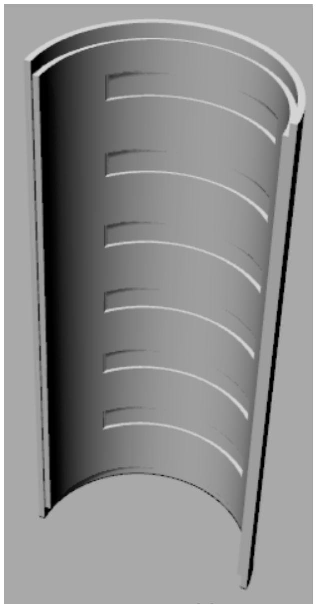


Figure 52. Dual layer internal pattern layout (line width not to scale)

8.2.4. Direct-Milled Bristles

While direct-milled bristles would not grant any flexibility in terms of arch dimensions, they would hopefully make a large number of arches unnecessary: after all, they could theoretically be made to fit to any dentition that physically fit within the mouthpiece. The following uncertainties are of importance here:

- Bristles perform differently based on length. Long bristles are more flexible, while short bristles are more abrasive and likely to damage enamel and gums. The range of acceptable lengths of bristles determines how many dentitions can make use of a given mouthpiece, before a new arch is required.

- Unlike the other customisations, which could be applied at any point in the mouthpiece, bristles can only be milled if they are actually there. If the frequency of the bristles happens to align with the width of an individual's teeth, the resulting pattern may lack certain necessary features.

Practical tests are not as relevant here as with the other tests, as the manufacturability itself is less uncertain. Instead, a comparison of dental arches and their corresponding bristle lengths can give some insight into the practicality of this solution.

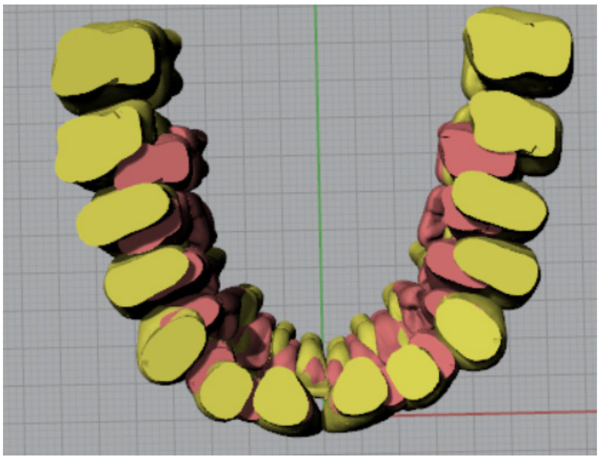


Figure 53. Comparison of a P10 caucasian female and a P90 African male (arch width + depth)

8.2.4.1.. Evaluation

Comparing two extremes in a multicultural dataset (P10 Caucasian female compared to P90 African male) using the dental reconstruction algorithm described in section 5.3 yields the result shown in image 48. The image illustrates the relatively small variation in arch width at any given point compared to the depth of the arch.

That being said, width variation can, in extreme cases, exceed 5mm. Especially when such a point overlaps with a pocket, this can result in exceedingly long bristles when using a single base model.

When using multiple base models, however, another problem occurs. As demonstrated by Papagiannis & Halazonetis (2016), the covariation of the maxillary and mandibular arch is only a relatively low 33%. This means that a single user may require different base arches for the mandible and maxilla.

Consequently, the main advantage of this technique (the fact that its manufacture is simpler than that of its counterparts) is undermined by the fact that every additional base arch results in an exponential increase in the number of complete mouthpieces that must be pre-moulded.

8.3. Selection

Using these data, a few early-stage decisions can be made:

- Both dual layer manufacturing and selective mesh adhesion are not viable in their current state. A solid mesh is too restrictive in the expansion of the sheet, while two equivalent superimposed layers have too little effect compared to the overall expansion.

- FDM manufacturing, while offering the greatest freedom, cannot be confirmed or disconfirmed within the constraints of the current project due to the complexity of the issue. Given this information, the method cannot reasonably be expected to be implemented before the deadlines set in the list of requirements.

- Direct-milled bristles are entirely feasible, but should be considered a back-up/secondary option due to the underlying necessity of a large number of moulds and its lack of geometric freedom.

Consequently, since none of the concepts satisfy the demands set in the project brief, a second iteration is implemented to build on the concepts of mesh adhesion and multilayer actuation.

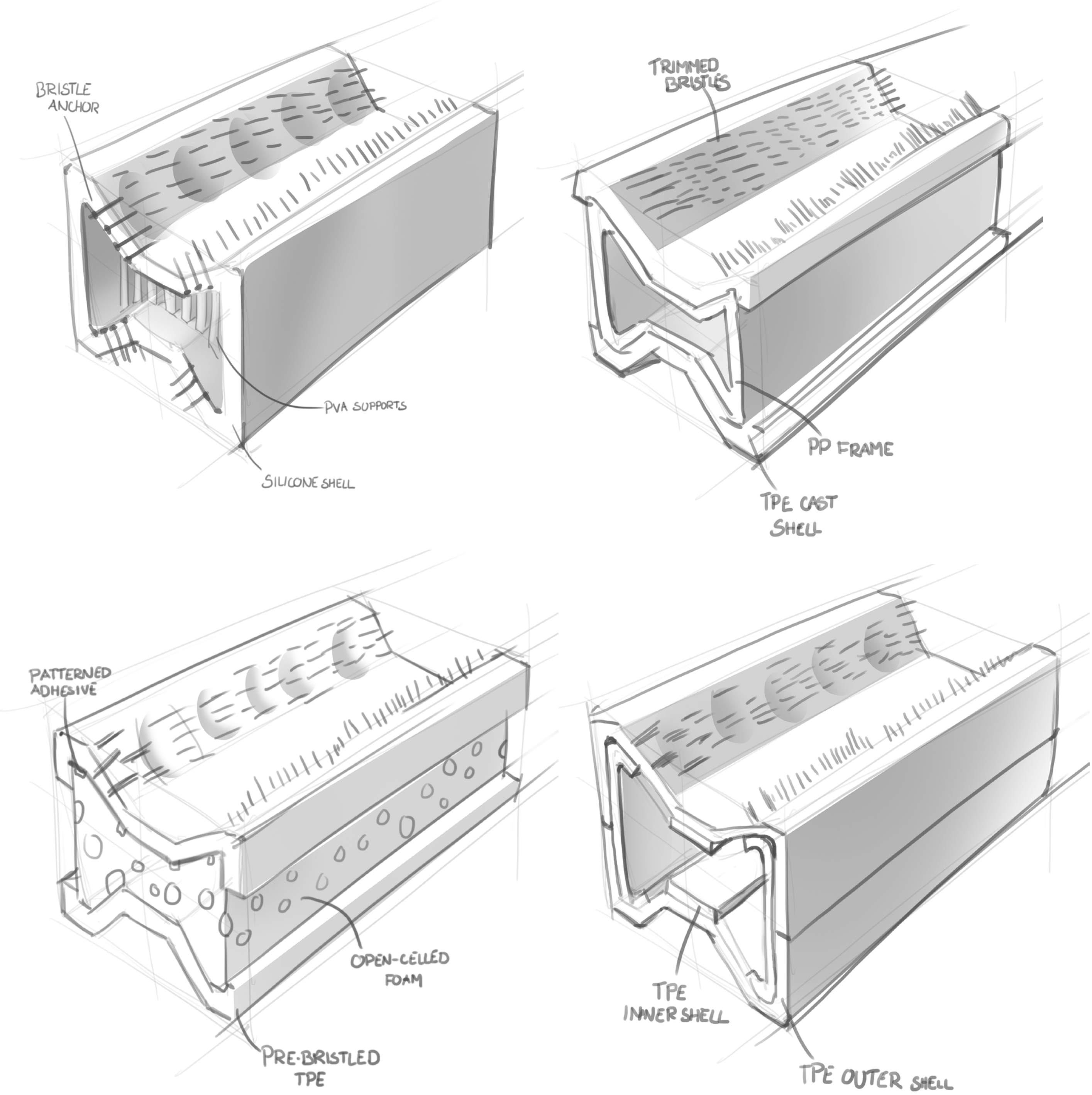


Figure 54. Cross-sections and surface properties of the four 1st-stage concepts.

09. 2nd Stage Synthesis

Weaknesses of the first iteration are ideated upon to create more viable prototypes. These include TPE laser etching, thermoformed form-fitting surfaces, and FDM-actuated form-fitting surfaces. Based on experimentation using a standard denture, contact is effectively optimised using the form-fitting surfaces. FDM frame manufacture provides the most geometric freedom.

Following the conclusions drawn from the first iteration evaluations, we can develop a range of concepts which take these possible limitations into account. This iteration again involves divergence, rapid prototyping, and selection.

This process uses more advanced full-contact prototypes to evaluate whether the actuation principles work as suspected in curved geometry.

9.1. Divergence

Ideation is approached by establishing the strengths and weaknesses of the ideas generated in the first iteration, establishing possible adaptations of these ideas to exploit the strengths or mitigate the weaknesses, and then combining these ideas into central concepts. For the full ideation pages, see the appendix, section 09.

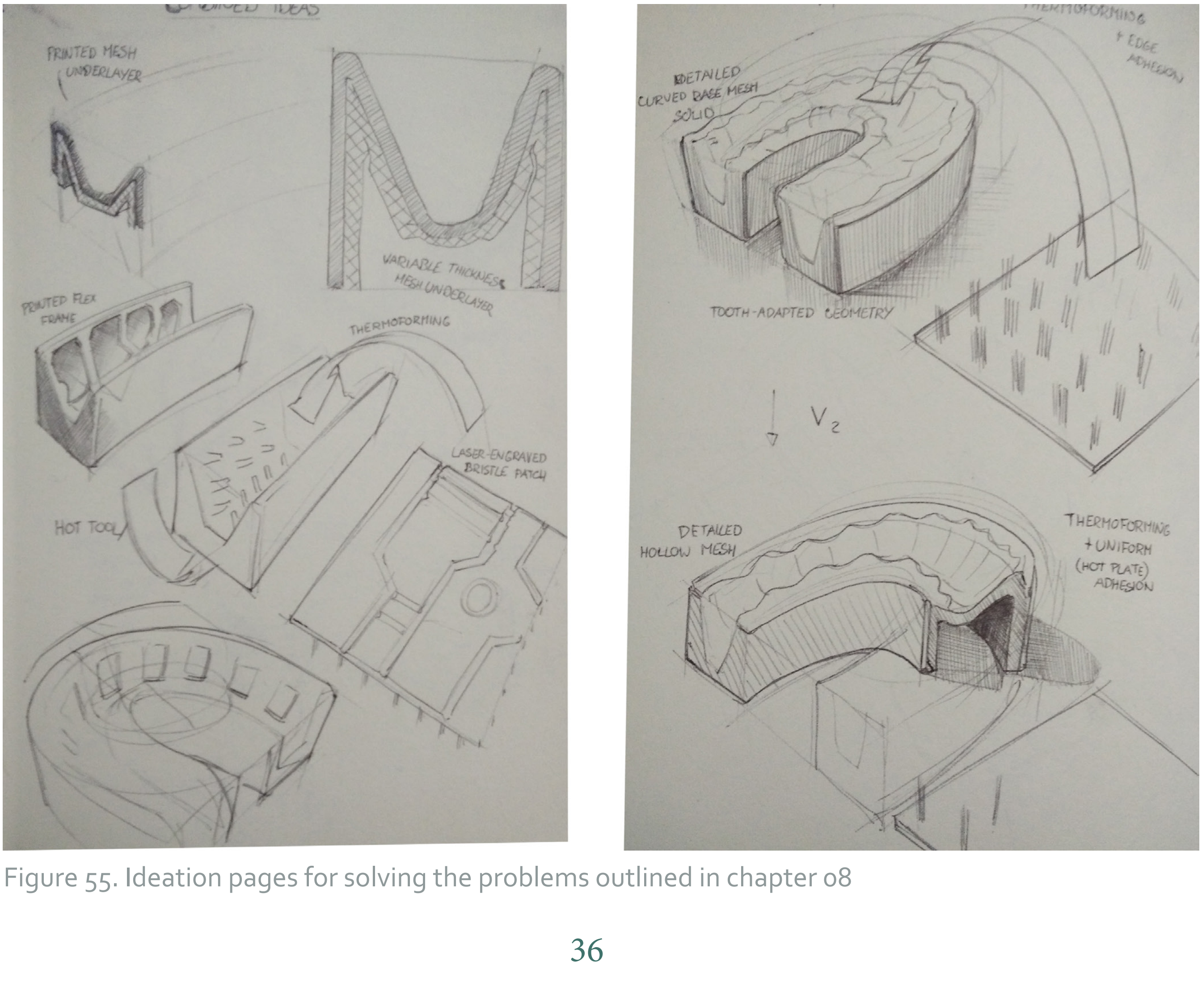


Figure 55. Ideation pages for solving the problems outlined in chapter 08

Resulting from this combination and reduction process are the following concepts:

9.1.1. Engraved frame patching

Using laser etching to improve potential resolution and thickness differences, a pre-bristled TPE patch is patterned conforming to the user's teeth. Subsequently, this sheet is thermoformed over an arch-fitting additively manufactured frame, and tool-welded into place.

The printed frame can contain custom geometry to provide specific anchor points onto which the sheet can be connected, reducing expansion at particular locations.

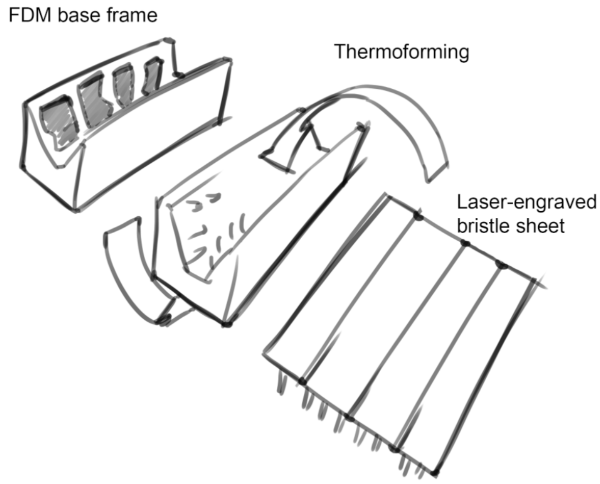


Figure 56. Engraved frame patching

9.1.2. Stationary mesh form fitting

A printed arch is produced according to the desired pattern of the mouthpiece expansion, including ridges for the pockets and gum lines. The material of the arch is meshed to enable free air transition. A standard bristled sheet is thermoformed over this arch, and adhered to the edges (but not the bristled sections). Inflation actuates the bristled sheet, but the core mesh itself remains stationary.

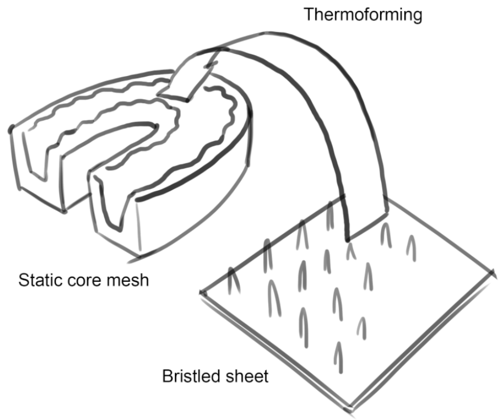


Figure 57. Stationary mesh form fitting

9.1.3. Flexible frame form fitting

A printed arch is produced, much like the stationary mesh, with two major differences: this frame is kept sufficiently thin and made out of TPE to allow for flexibility, and it is fully adhered to the TPE sheet formed over it during the thermoforming/welding process. The result is effectively a dual-layered sheet system, while retaining greater flexibility over both the thickness and the shape of the item.

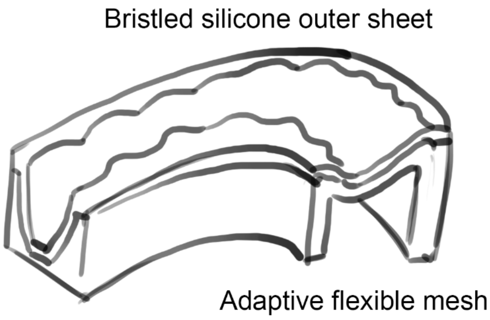


Figure 58. Flexible frame form fitting

A note on sheet bristles

In the context of the project brief, Dental Robotics noted that the development of functioning and thermoformable bristle sheets (TPE sheets with tufts of nylon fibres) themselves should not be considered part of this graduation project. While the ability to implement nylon bristles is a necessity, the process itself has not yet been perfected.

Nonetheless, this report considers nylon bristle sheets a useable resource in the near future (although naturally, alternative options are always left open).

Because the sheets are not yet available in their finished form, some details (such as available bristle density and length) are unknown. All designs are made to take these uncertainties into account.

9.2. Prototyping

Whereas the first generation of prototypes was based on simple visual evaluation, the distinctions between these manufacturing techniques are subtle enough that the prototypes equire some comparable evaluation method. For this reason, prototyping is performed according to the following principle:

For each manufacturing principle, a half mouthpiece is designed and built by hand to fit a particular dental impression. In absence of thermoforming bristled sheets and manufacturing capabilities, cast silicone outer sheets are used instead.

These sheets are then inflated against the denture they were designed to fit. Contact spray is used to illustrate the extent of mouthpiece-to-denture contact.

Implementing these approximations of the three working principles results in the prototypes shown in figure []. The silicone sheets are all executed in shore 25. Subsequently testing the actuation of these mouthpieces is done by inflating the mouthpieces with a constant volume of air from a syringe.

9.2.1 Engraved frame patch

The patch is executed in this case as a .8mm thick silicone sheet, with 2mm high ribs angled to coincide with the middle of each tooth face.

Inflating this interpretation of the engraved frame patch results in an expansion pattern which is nearly indistinguishable from the expansion of a non-modified mouthpiece: no additional expansion is visible in the mouthpiece at the thin-walled sections.

The results of this expansion pattern are also clearly visible in the contact spray results: contact is made with the tooth faces, but not with the interdental regions.

It should be noted that this is only one possible arrangement of thicknesses out of effectively infinite combinations of patterns, thicknesses, and shore values. That being said, due to time and resource constraints within the process this iteration will be used to estimate the overall viability of the manufacturing method.

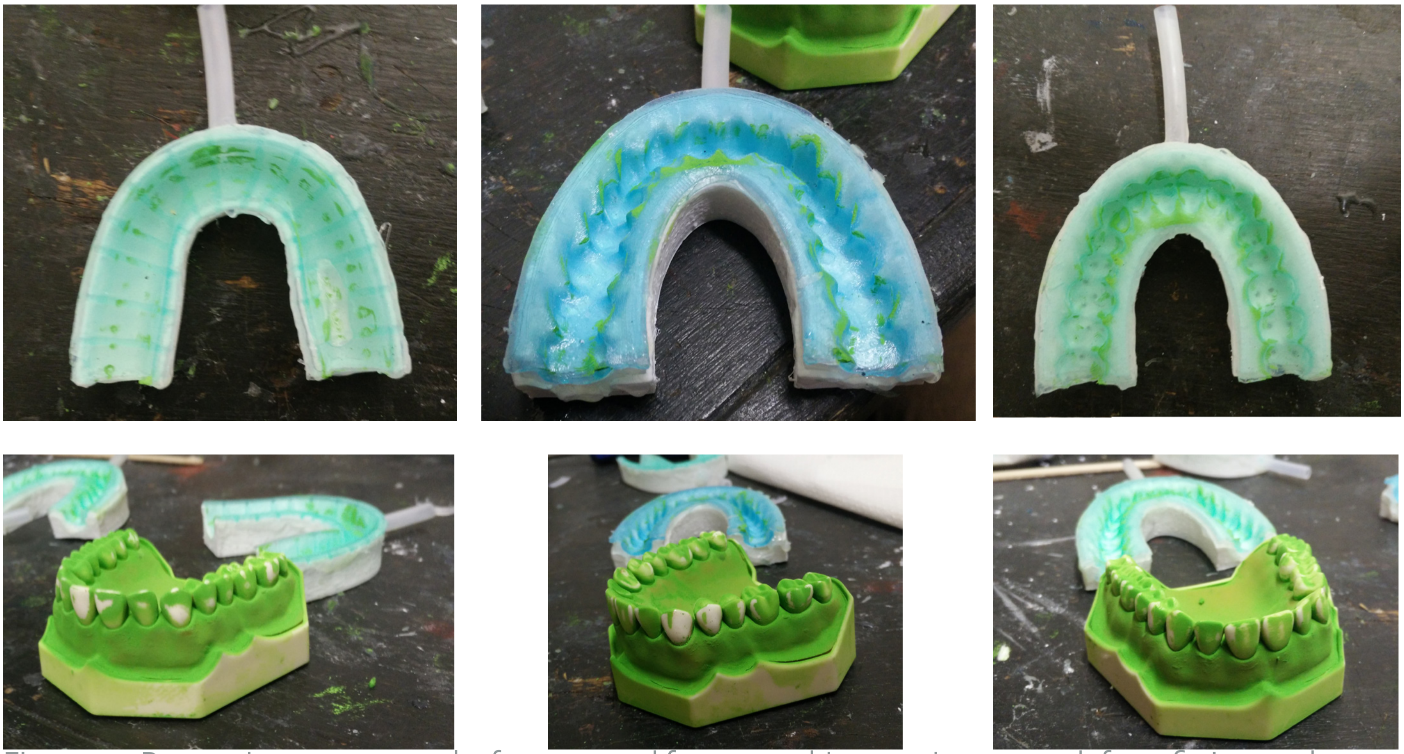


Figure 59. Respective contact results for engraved frame patching, stationary mesh form fitting, and flexible frame form fitting.

9.2.2. Stationary mesh form fit

The stationary mesh is executed as a solid PLA outer shell with a tight-fitting hollow PLA inner filling, in which regularly spaced holes allow for the airflow. The silicone sheet is offset from the teeth by 1.5mm, and has a thickness of .8mm.

Compared to the engraved patch, the expansion of the stationary mesh prototype is visibly lower under the same air input (i.e. the pressure in the mouthpiece appears to be higher for the same deformation). Due to the inherent proximity to individual teeth, however, total contact area is not visibly lower.

Figure 60. Close-up of stationary mesh prototype

Contact with the interdental regions is far more obvious than in a conventional mouthpiece, while contact with tooth faces is reduced. This may be due to the increased curvature of the mouthpiece surfaces around the interdental regions heightening the chances of direct contact with nearby tooth surfaces.

Compared to an unactuated mouthpiece, the prototype appears to achieve relatively little contact through inflation: most contact areas are touched simply upon insertion.

9.2.3. Flexible frame form fit

A directly printed, high-shore TPE frame is fully adhered to the silicone bristle sheet, which is the same cast used in 9.2.2. The resulting prototype's actuation is heavily reduced, requiring notably more pressure compared to either of the other prototypes for a minor expansion.

Again, however, due to the small surface-to-tooth distance, a large expansion is not necessary, and the actuator makes a relatively large amount of contact throughout the interdental regions.

A full set of analysis photographs can be seen in the appendix, section 09.

9.3. Selection

Considering that under the established criteria, the mouthpiece performance is largely based on the contact with the interdental and gum line regions, the engraved sheet does not appear to provide any benefit. Although its performance could probably be improved through changes in design, thickness, and material choice, such exploration does not fit within the scope of this project.

The choice, then, is to be made between using a thermoformed sheet of TPE as an actuation medium, or using printed TPE as the main actuator. Although the experimental setup was not well suited to quantification, there was no immediately visible difference in contact area between the mouthpieces.

Of the manufacturing principles, FDM printing benefits from a major advantage: control. Without any increase in manufacturing complexity or cost, variations in thickness and geometry can be reliably introduced. Thermoforming, on the other hand, can be difficult to control, especially when the exact dimensions of the mouthpiece are not known beforehand.

Based on these criteria, flexible frame form fitting appears to be the most viable of the demonstrated manufacturing principles.

Figure 61. Close-up of flexible frame prototype

10. 3rd Stage Synthesis

Previous concepts are broken down and redefined in terms of components and their manufacture/assembly. Four concepts are the result, each conforming to individual dental geometry through a different mechanism. All are prototyped for manufacturability. FDM sheet thermoforming combined with solvent or sealant assembly is picked as the most likely solution.

As the level of complexity in the synthesis approaches that of the final product, it becomes increasingly necessary to simulate a more complete approximation of a full mouthpiece. For this reason, the final synthesis stage consists of the production of entire, functional mouthpieces using the closest available manufacturing principle.

10.1. Divergence

Following the conclusions from chapter 9, it is all but certain that the manufacturing principle will need to enable a bristle surface which follows the curvature of individual teeth.

Based on this information, and by splitting up the mouthpiece into its constituent components, it is possible to generate a morphological chart which represents all currently viable combinations of manufacturing methods. Compared to previous iterations, these combinations also take into account the nature of the bristling sheets and both assembly and surface finishes.

Cross-combination of these manufacturing methods ultimately leads to four manufacturing concepts, based on FDM manufacturing, bristle trimming, glass transition deformation, and SLS manufacturing, respectively.

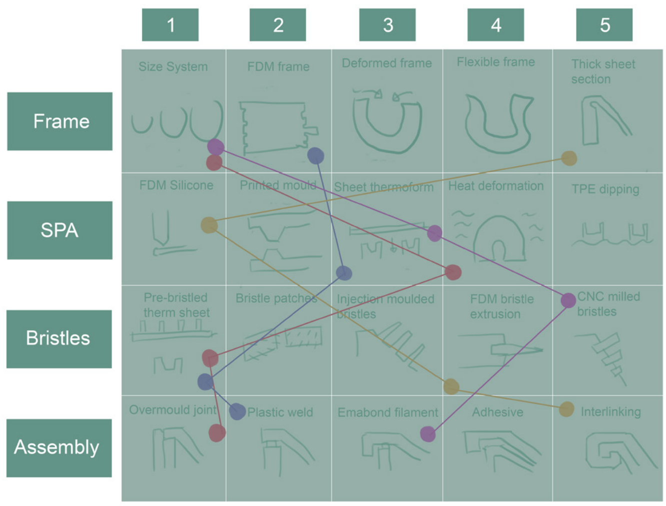
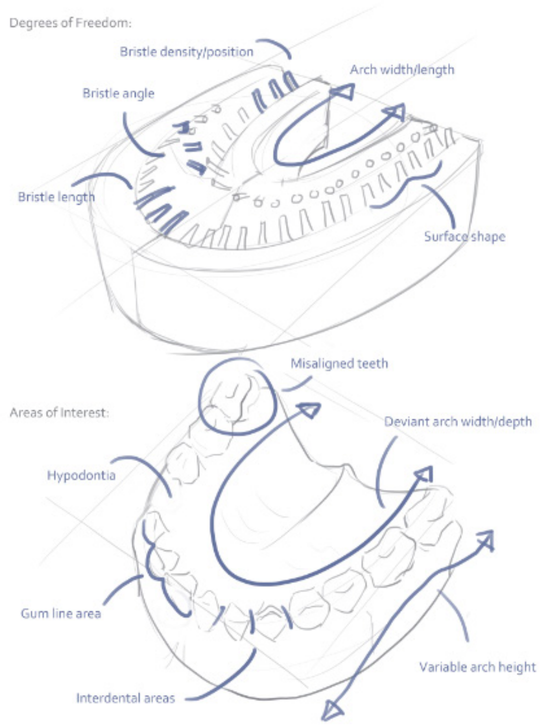


Figure 62. Permutations of a component-separated process overview. The full-sized version can be seen in the appendix.

Figure 63. Available parameter space and anatomical variations to be supported.

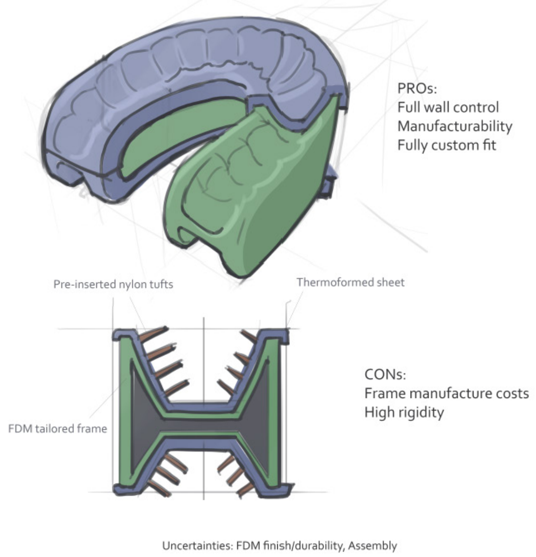


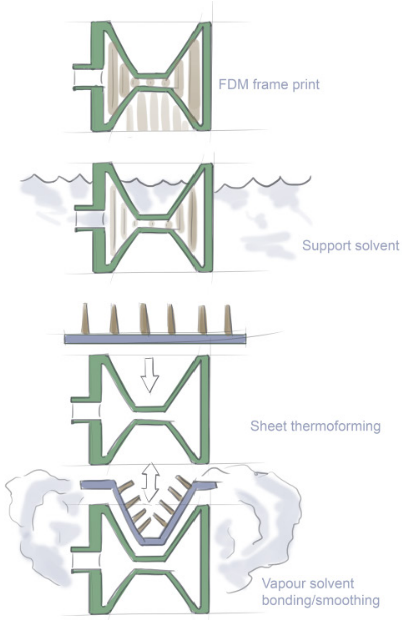
10.1.1. FDM sheet thermoforming

Directly based on a method discussed in chapter 9, this concept consists of a semi-flexible TPE frame (manufactured using basic FDM printing) form-fitted to the dental surface target, over which a TPE sheet with nylon bristles is thermoformed. PVA supports are used for the FDM print to guarantee that the internal material can still be removed.

The sides of the FDM print are relatively thick and completely solid, while the dental contact areas are patterned to guarantee optimal local flexibility where necessary. Vapour solvent is used for dual purposes: both as an adhesive between the TPE components , and to smooth and seal the solid outer walls (see Ch. [12]).

Figure 64. FDM sheet thermoforming



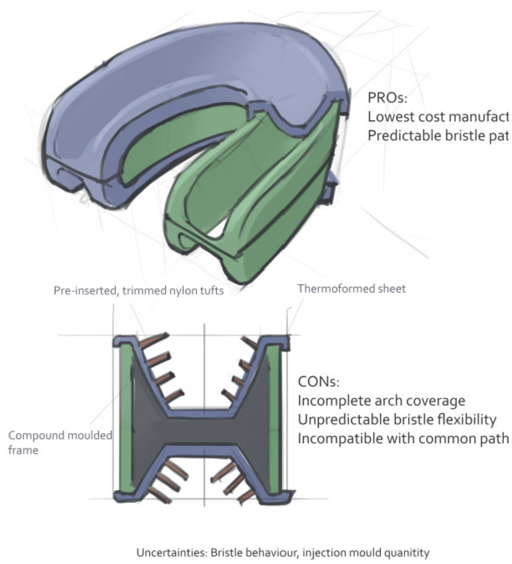


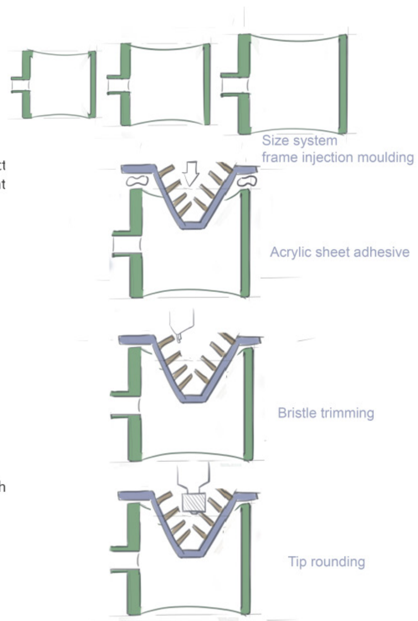
10.1.2. Bristle trimming

The bristle trimming concept consists of a two-part injection moulded frame, onto which a thermoformed sheet is glued. Subsequently, the bristles are trimmed along a pattern conforming to the outer surface of the dental scan, resulting in bristle tips which perfectly align with their intended targets.

The frame is assembled from a maxillary and mandibular part to reduce the required number of injection moulds. Corresponding thermoformed sheets are made for each of those parts. After trimming, the bristles must have their tips ground down to prevent enamel damage. This means that the concept may require two 3-axis systems.

Figure 65. Bristle trimming



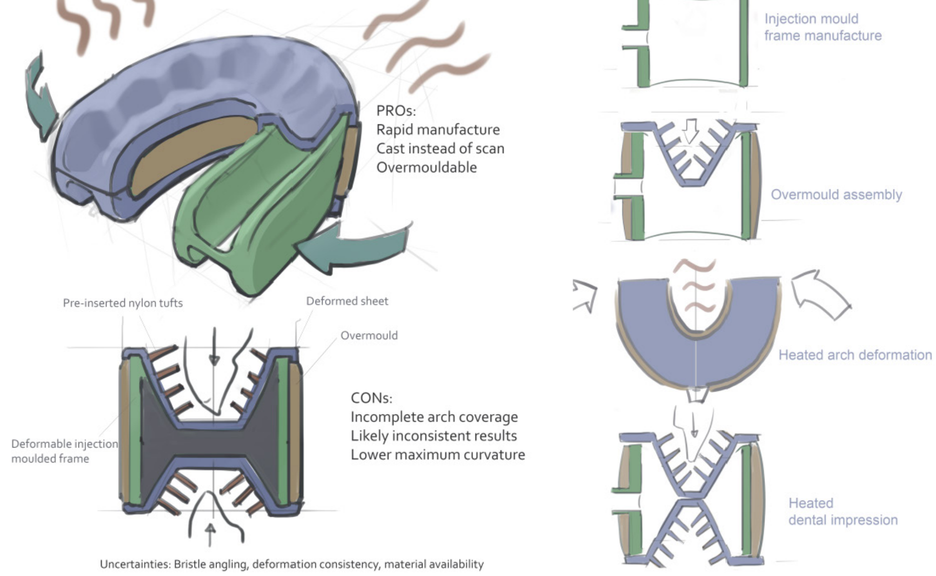


10.1.3. Deformable base model

Relying on methods which are currently in use for the base model of the mouthpiece, an injection moulded mouthpiece is formed. A relatively shallow, full-TPE bristle sheet is overmoulded onto the frame. The temperature is increased above the glass transition temperature of the frame, after which the arch is deformed to fit the required dental arch.

Subsequently, the temperature is lowered until it only exceeds the lower glass transition temperature of the TPE sheet. A dental impression is then pressed onto either side of the model while pressure is applied to the mouthpiece, leaving an indentation which conforms to the dental shape. This appears to be the most unproven of the four prototypes.

Figure 66. Deformable base model

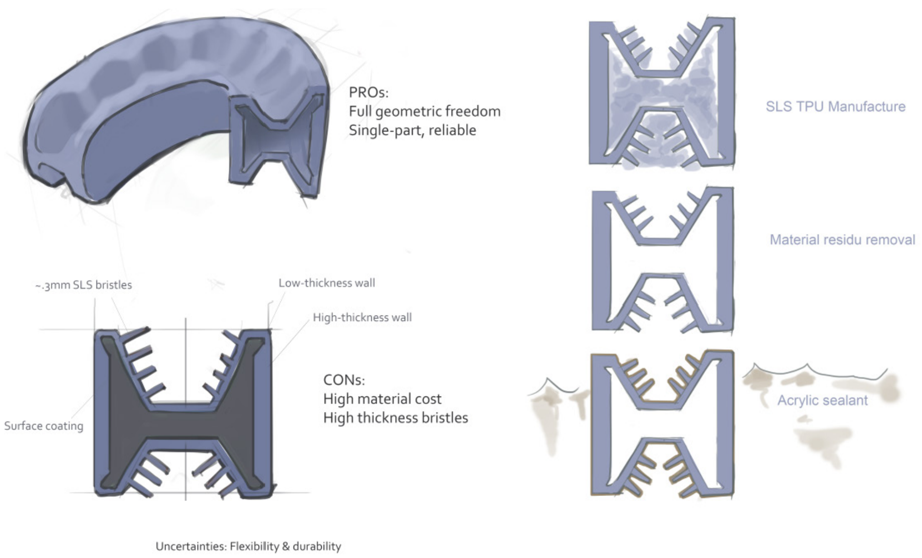


10.1.4. SLS fabrication

This method relies on a relatively new material development: SLS fabrication of highly flexible TPUs. The full mouthpiece, incuding relatively thick bristles, is sintered from a single material. Due to the nature of SLS, this allows angled bristles and inner chambers to be printed without support material. The rest material is removed through the inlet.

The surface of SLS fabricated products is relatively coarse, and not typically airtight, so an acrylic or TPE-based sealant is required to finish the product. This further adds to the minimum diameter of the bristles, as well as the costs of manufacturing --which, given the cost of SLS machinery and materials, may well be considerable.

Figure 67. SLS fabrication



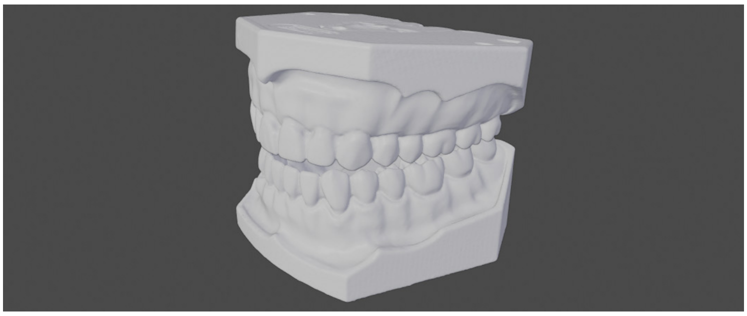


Figure 68. Frasaco model scan

10.2. Protoyping

For this prototyping stage, mouthpieces are designed to fit a standard dental model from Frasaco, which was scanned and processed using the same procedure that was previously applied to dental casts.

10.2.1. FDM Sheet thermoform

The frame model for the FDM sheet is designed and printed as a 3mm offset of the individual tooth surfaces, given a thickness of one millimeter for quick printability. No patterning is applied yet to improve surface flexibility.

In absence of soluble support material, the print is instead executed in two halves. This enables the support material to be removed from the print internalities.

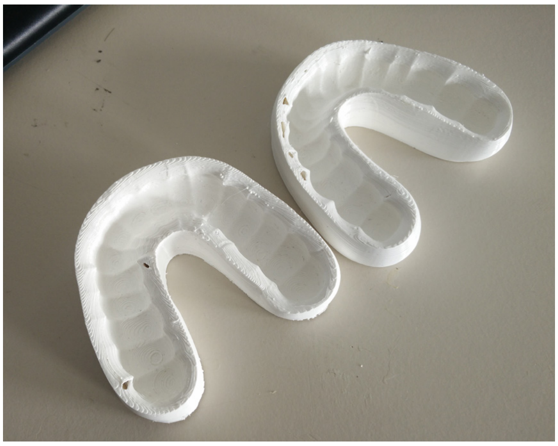


Figure 69. FDM mandible and maxilla actuator

The TPE is executed as a direct-printed FDM sheet for testing purposes, then applied to the frame. The resulting components are glued together and checked for airtightness.

The resulting assembly is capable of deforming to fit the mouthpiece, though only under considerable pressure--more than the traditional handle can supply. The necessity of a flexible surface structure is obvious.

10.2.2. Bristle trimming

Bristle trimming cannot be tested fully without a 3-axis setup which is frankly too time-consuming to make. Instead, the principle can be tested using a traditionally manufactured mouthpiece in which the lengths of the bristles have been adapted to coincide with the surface of the Frasaco model. An SLA-printed mould is used to injection mould, and then overmould, the flexible membrane.

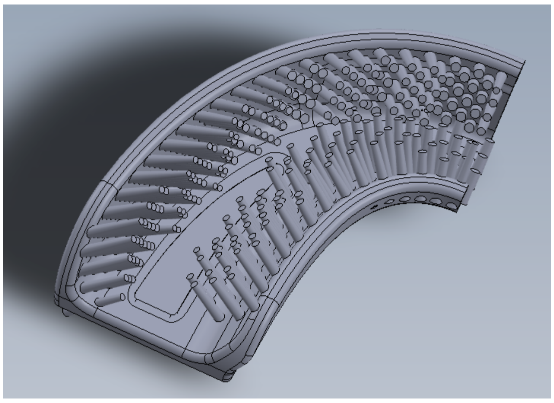


Figure 70. Bristle length-adapted mouthpiece

Manufacturability is not the main question in this case: it is possible to directly compare contact performance with the main mouthpiece to see whether the aligned bristles are more suitable.

10.2.3. Deformable base model

A basic frame, which deviates from the desired Frasaco by several millimeters, is FDM-printed. The slightly pre-formed bristle sheet is stretched over this frame.

Figure 71. Frame/sheet assembly after being deformed

The desired outline of the frame is marked on two sides, and the frame is stretched under a temperature of 145 degrees Celsius until the outlines have been reached.

Figure 72. Deformed frame with bristle sheet

Under this same temperature, the sheet is impressed with the dental model. The heat gun is then removed and the model is allowed to cool.

Figure 73. Impression left under high temperature

10.2.4. SLS fabrication

Unlike the other concepts, the means to create an SLS model are not directly available. As such, this model must be purchased from an external supplier.

The ideal material for SLS manufacturing is Duraform Flex, an SLS-processable TPU. Unfortunately, the lead times of these external suppliers vary greatly by material, meaning that this material can not be applied within the constraints of the project.

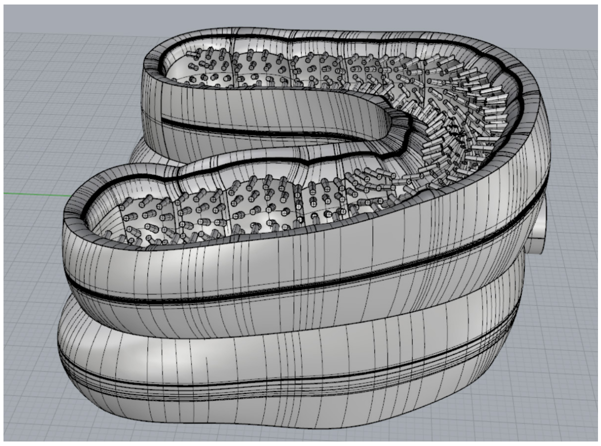


Figure 74. Surface model for SLS printing

Focussing on the viability of manufacturing itself, rather than full actuation, allows for the use of non-elastic materials like Nylon 6-6, which drastically reduces manufacturing costs and lead times.

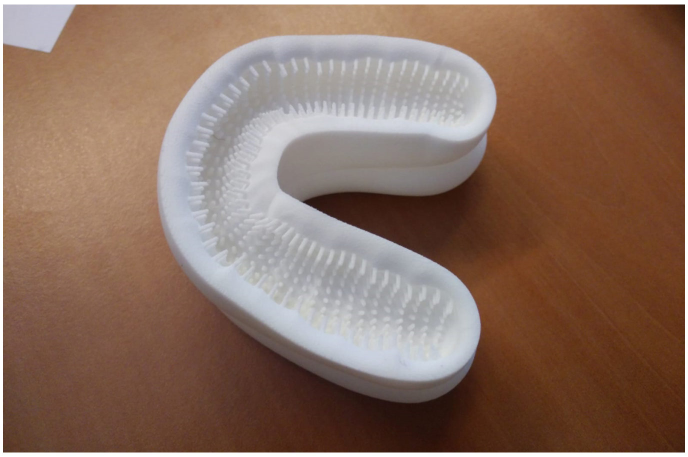


Figure 75. Nylon SLS model

Despite the manufacturer's suggestions that the product might fail due to powder residue or bristle breakage, the finished prototype appears to be nearly flawless: aside from some modelling imperfections, the print is airtight, every bristle is present and sturdy, and no residual powder appears to remain in the mouthpiece.

10.3. Selection

Based on this prototyping stage, both FDM/ thermoforming and SLS manufacturing are viable production technologies. Their resulting geometries are sufficiently detailed and to provide the desired bristle orientation and placement.

Trimmed bristles do not appear to provide the interdental contact improvements that were seen in surface-adapted mouthpieces during the second iteration stage. Speculation on the cause of this difference might be that the low bristle density reduces the chances of any bristle actually existing near the interdental regions, or that the relatively long interdental bristles are too flexible to make solid contact.

The deformable base model appears to be difficult to shape accurately without misforming either the sheet or the frame. While application of different materials or manufacturing methods might improve its performance yet, it seems reasonable to reject the concept for the moment.

The concept choice, therefore, comes down to the choice between FDM/thermoforming and SLS.

An immediately obvious distinction is that of material and operating costs. High-end FDM TPUs cost in the region of 70 euros per kilogram (colorFabb, 2019) not counting support material, and can be printed with machinery worth around a thousand euros.
SLS TPEs, meanwhile, cost around 170 euros per kilogram (Sinterit, 2019) for desktop machines not counting waste material or sealant, and are processed with machinery worth around six thousand euros.

Strictly speaking, FDM/thermoforming is also the only manufacturing technology that satisfies the requirement of being able to handle nylon bristling.

Based on these properties, the preliminary choice is made to use FDM/thermoforming as the manufacturing method. Dental Robotics is advised, however, not to discount SLS manufacturing as an option. The technique could probably be implemented sooner, and possibly more reliably, than

11. Data Processing

To reduce the costs of processing individual sets of teeth, an algorithm is implemented to automatically detect dental features and construct the corresponding surfaces. Region growing is selected as the most accurate and practical approach, albeit at the cost of considerable processing time. The presented algorithm is a proof of concept, but requires further development.

In order to create versions of the mouthpiece designed in chapter 3 for every dental scan, manual design would be far too labour-intensive. For this reason, this chapter will discuss the automation of this process.

Included in this chapter are a summary of the data which must be extracted from the dental scan, a discussion of the properties of the meshes received, a description of the process for finding interdental regions and gum line regions, respectively, and validation of these processes on several available dental scans.

Note that all the work in these chapters was done, due to resource constraints, using scans of dental casts rather than direct scans with intra-oral scanners. While these are not fully interchangeable in every respect, the results discussed here should still transfer easily to other scanning methods.

All feature detection was executed using Rhino 5 SR14 in combination with Grasshopper 0.9.0076.

For the full grasshopper definitions, python code, and explanations of sub-problems, see appendix section 11.

11.1 Required information

The following data are necessary to create the base surface of a tooth-fitted mouthpiece:

- The curve that describes the path followed by the intersection between the teeth and the gingiva

- The curve that describes the path followed by the 'cusps' (the upper edges) of the teeth

- The surface of the teeth that lies between these boundary curves

Visually, the borders that describe these boundary curves are very easy to distinguish. Retrieving these data from an STL file, however, is not possible directly.

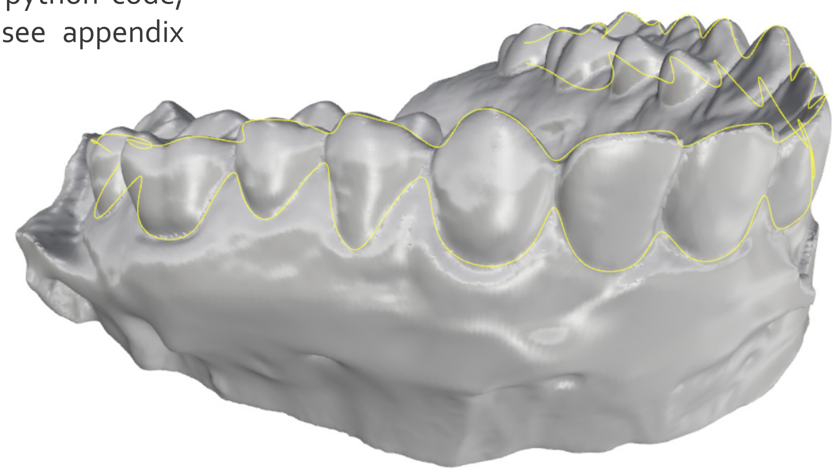


Figure 76. Target dental curves to be extracted from facial mesh

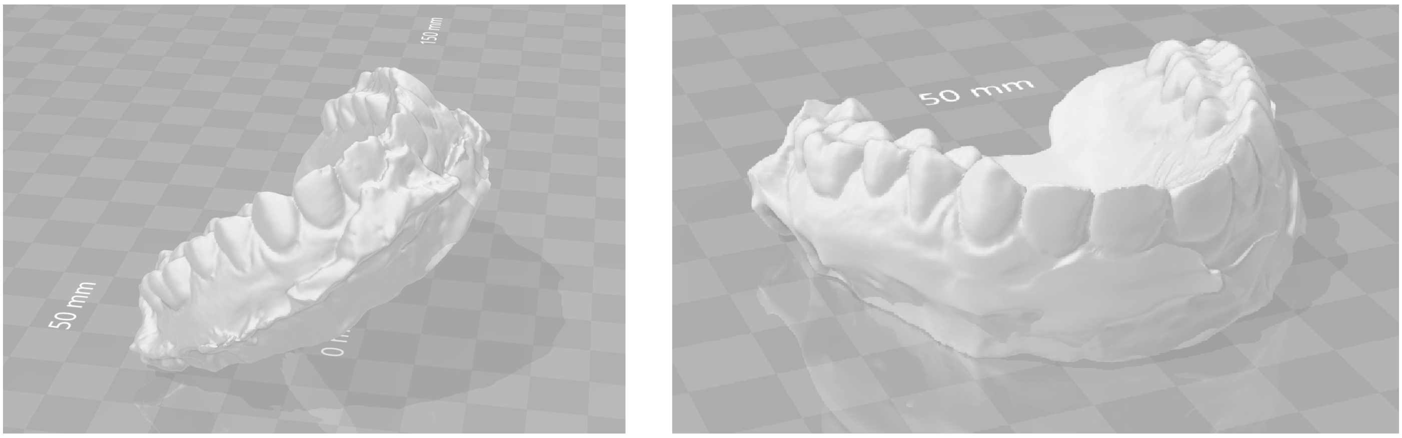


Figure 77. Manual clean-up process: air bubbles and breakages are removed, and the model is aligned.

11.1.1. Mesh properties

The mesh consists of a high-resolution batch of 3D points in space which are interconnected using edges. Three edges enclose a flat triangular face. Depending on the method used for the scanning process, the mesh can be either open or closed.

The main regions of interest--interdental lines, tooth cusps, and the gingival line--are all characterised by high local curvature. In the case of the cusps, this curvature is convex. In the case of the interdental regions and gum line, this curvature is concave.

The scans seen in this chapter were made using an Artec Spider, at a resolution of 0.1mm. Models were rebuilt later to reduce the computational intensity of the processing. In the case of dental cast scans, like those used for this project, imperfections in the casting process often result in the inclusion of air bubbles or other defects. For this reason, any mesh used in this process was first cleaned up using the sculpting tools in Blender. This means that some scans of heavily damaged casts are approximations of the original teeth, rather than a perfect copy.

If the scan was instead made directly using a colour-sensitive intra-oral scanner, such as the 3-shape TRIOS, the distinction between teeth and gums would be incredibly easy to make. Unfortunately, given the penetration rates of such scanners (or indeed any intra-oral 3D scanner) in the market, the gum line extraction must be capable of working with untextured scans.

Figure 78. Rebuilding the mesh reduces workload and removes minor noise.

11.2 Interdental detection

In reality, teeth are distinct bodies which are at most occasionally in contact with one another. Due to the superficial nature of 3D scanning, however, meshes of teeth typically result in a continuous mesh surface in which the boundaries between teeth are marked by a high concave curvature.

Using a plane to intersect the mesh body results in an intersection polyline which follows the same curvature pattern. This way, the spaces between individual teeth can be recognised.

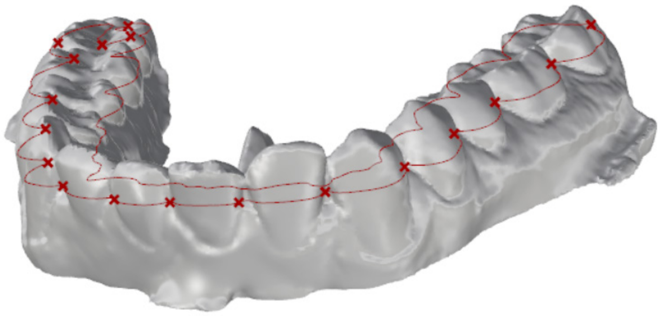


Figure 79. Interdental planar intersection

This technique is reliable, but depends on the planarity of the teeth: if the teeth are non-planar, a suitable non-planar surface is necessary to find an intersection curve which includes all teeth, but excludes the gums.

Finding such a surface is possible by using an outline projection: the upper bound of this outline is defined by the cusps of the teeth, and can be simplified and offset to return a curve which reliably intersects with the teeth.

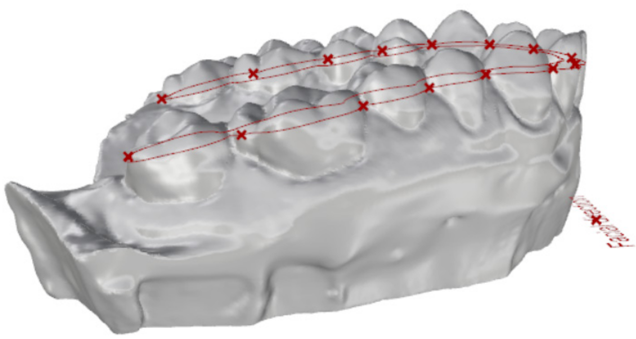


Figure 80. Non-planar intersection

11.3 Gum line detection

Evaluating the gum line is a more difficult problem than the interdental regions. Dividing a dental scan between individual teeth and the gums is a topic on which a wide variety of approaches have been applied, including artificial neural networks (Raith et al., 2017), harmonic fields (Liao et al., 2015) and morphologic skeletons (Wu et al., 2014).

Many of these approaches are either too advanced given the scope of this project, or depend on a large available repository of dental data. When taking these limitations into account, as well as the fact that full integrated segmentation is not necessary, two approaches prove to be promising: Projected Curvature and Region Growing.

11.3.1. Projected curvature detection

Using the same basic principle as the interdental region finding, it is possible to find an approximation of the gum line. This is performed by regularly dividing the established intersection line, and extending vertical lines from these points which are then projected onto the mesh. Evaluating these projected lines for the point of highest curvature result in a number of sampling points which can be used to approximate the gingival line.

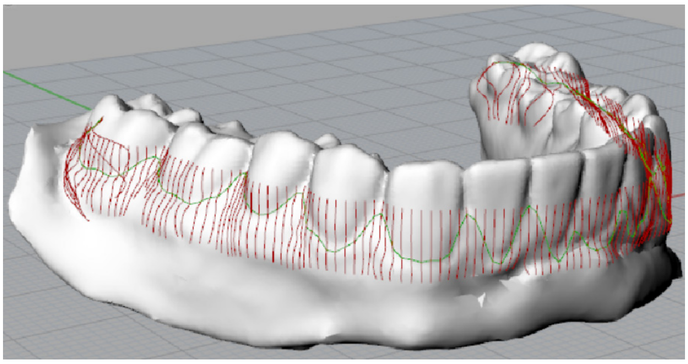


Figure 81. Vertical curves projected onto the mesh

The result is a gingival line which is typically accurate for regular meshes, but which is not robust to unusual tooth angles or tangencies.

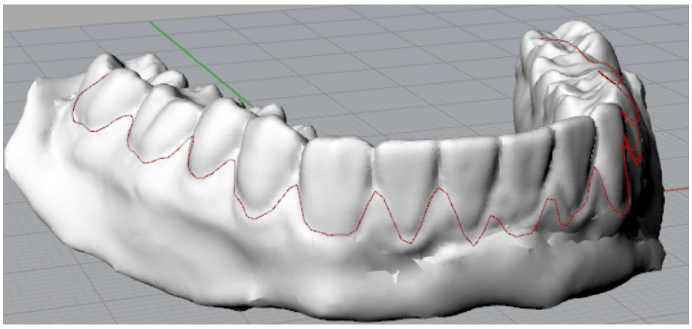


Figure 82. Low-curvature gums are not detected

11.3.2. Region growing

Region growing can be used to segment dental meshes, as described by Kim & Choi (2018). This approach relies on using a seed point for every tooth, gradually expanding outwards until a curvature threshold is encountered. Applying this methodology is considerably more resource-intensive than projected curvature, as it involves a large amount of recursive angle computation, but it results in more dependable segmentation.

Seed points can be found by taking the halfway point of the previously established intersection segments. Expansion occurs until either a very sharp convex curvature is encountered (signifying the dental cusps) or a more gentle concave curvature is encountered (indicating the gum line regions).

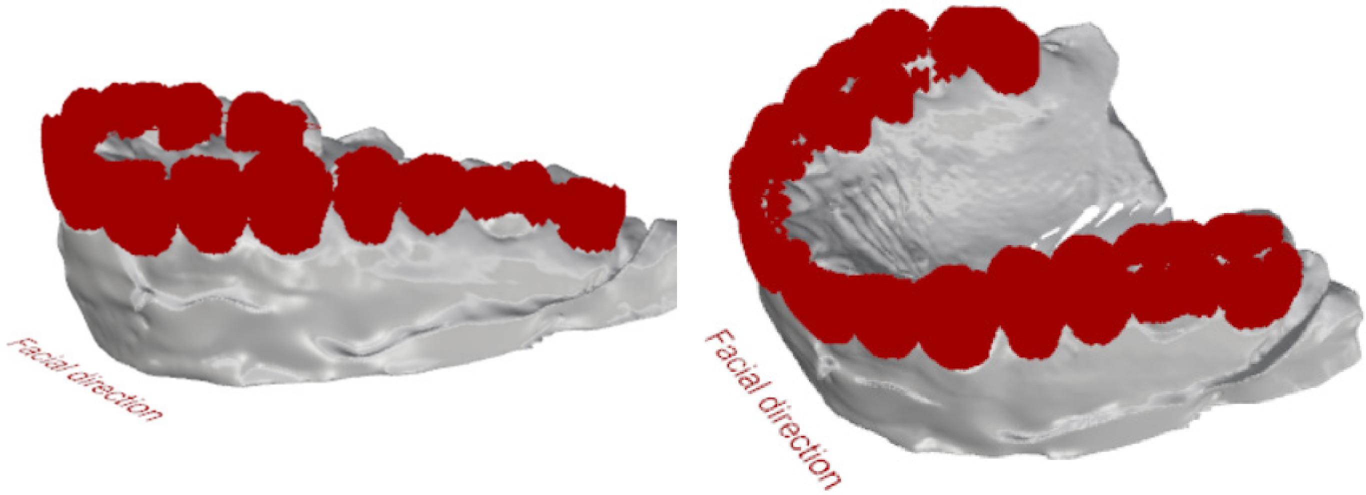


Figure 83. Region grown faces. The second image uses pre-sliced mesh segments to run roughly two orders of magnitude faster.

Running this algorithm on the entire dental scan is prohibitively time-consuming, segmenting the facial surfaces of a maxilla scan in no less than a full hour. This time can be reduced by first using the intersection evaluation to pre-segment the mesh into more manageable 'slices' before applying the segmentation algorithm. The resulting decrease in array lengths massively reduces the amount of time spent on cross-referencing face lists.

Once the faces belonging to the dental surfaces have been established, they can be separated, and the curves describing their outer boundaries used as gingival lines.

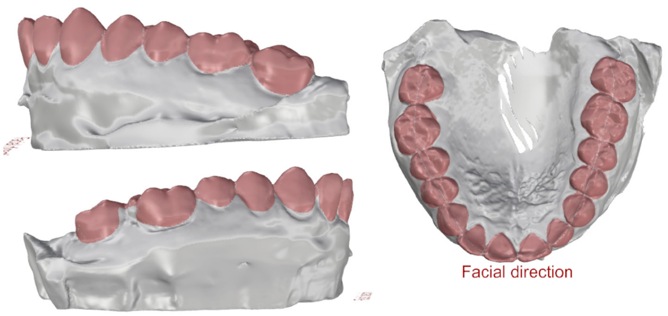


Figure 84. Final segmented mesh

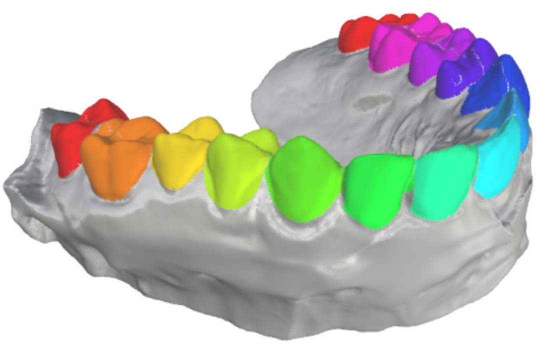


Figure 85. Individually marked dental meshes

11.3.3. Gum line evaluation

Neglecting the duration of the algorithm--which is of minor importance given its small contribution of the overall duration of the manufacturing process--region growing offers an improved performance in every aspect compared to projected curvature. Aside from improved accuracy and robustness, region growing also distinguishes between individual teeth, which provides some utility in the design process.

It is almost impossible to objectively evaluate this dental segmentation algorithm. Manually gathering the gum line from an unsegmented dental scan is approximation work itself, and as such the results do not provide a very reliable reference point to judge the scan by. Manually determining the gum lines results in an average Hausdorff distance of roughly .45mm for a fairly typical scan, but this error could be attributed to either one of the interpretations. For further validation at future stages, it may be useful to use a textured intra-oral scan for validation: textures can then be used to accurately draw the gum line.

Visual inspection of the segmentation reveals that the algorithm is largely accurate, but does not seem to handle unexpected high-curvature protrusions very well. Overflow and underflow of the gum line also appears fairly common. Future work to make this algorithm robust to more scans, including those with braces, sharply angled wisdom teeth, and asymmetric arch heights, falls outside the scope of this project.

11.4 Surface building

Unfortunately, the separated meshes generated in section 11.3 are not sufficient to construct a mouthpiece. Approximate surfaces need to be generated which can be used in future processing.

First, the 'cusps' (or upper sections) of the teeth must also be described using a curve. This can be performed fairly straightforwardly by taking the individual dental meshes, and taking their cross-sections at regular intervals perpendicular to the dental arch.

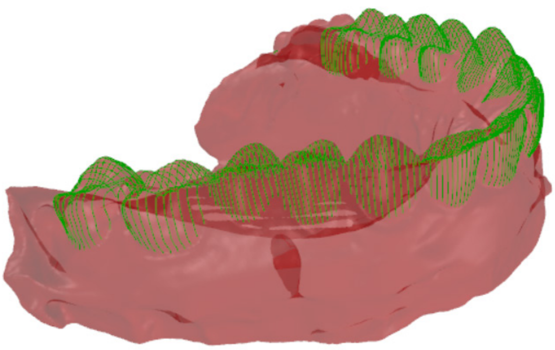


Figure 86. Perpendicular plane/dental mesh intersections

The outermost point on these curves on which the derivative is roughly zero describes a point on the facial cusp. The innermost point describes a point on the lingual cusp. Like the gingival line, these points are then interpolated and simplified to create a smoother, more manageable curve.

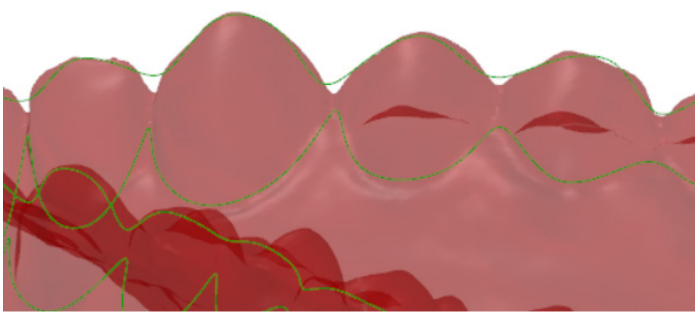


Figure 87. Curve through the nearest roughly-zero derivative points.

These curves are then once again subdivided using the interdental regions, resulting in the outer edges of the individual teeth. Guide curves are constructed using the underlying mesh, allowing NURBS surfaces to be constructed.

Offsets of the individual teeth are created, and interconnected using trimming and lofting actions. This results in a continuous polysurface that can subsequently serve as base geometry for implementing bristles and so forth.

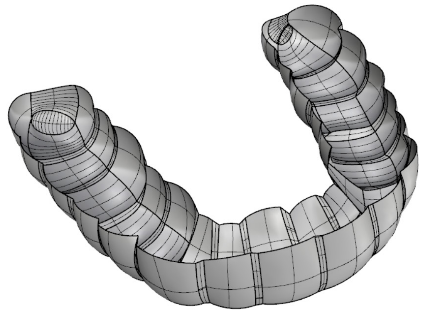


Figure 88. Mesh-derived polysurface

With additional work, it would be possible to fully automate the design of any of the proposed concepts from this polysurface. For now, the rest of the designs are performed manually for protoyping purposes.

11.5 Limitations

With every step that is taken in the process from scan to polysurface, some level of detail is lost. Region growing does not perfectly align with the gum lines, the subsequent curves are simplifications of reality, and the surfaces are rebuilt at several stages to mitigate local errors. As a result, the end result is not a perfect fit to dental anatomy -- though it still aligns accurately with the interdental regions and most gum lines.

The last step of offsetting the surfaces to allow for bristle lengths has the unfortunate side effect of reducing the interdental curvature. The logical conclusion is that, to maintain optimal bristle-to-surface contact, bristle length should be minimised as far as possible.

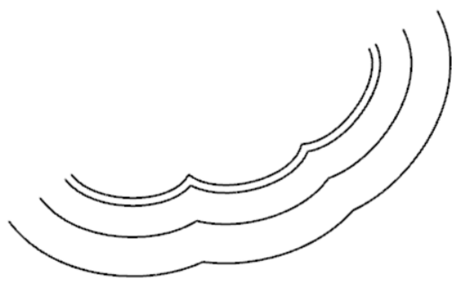


Figure 89. Loss of curvature detail for 1mm, 3mm, and 5mm offsets

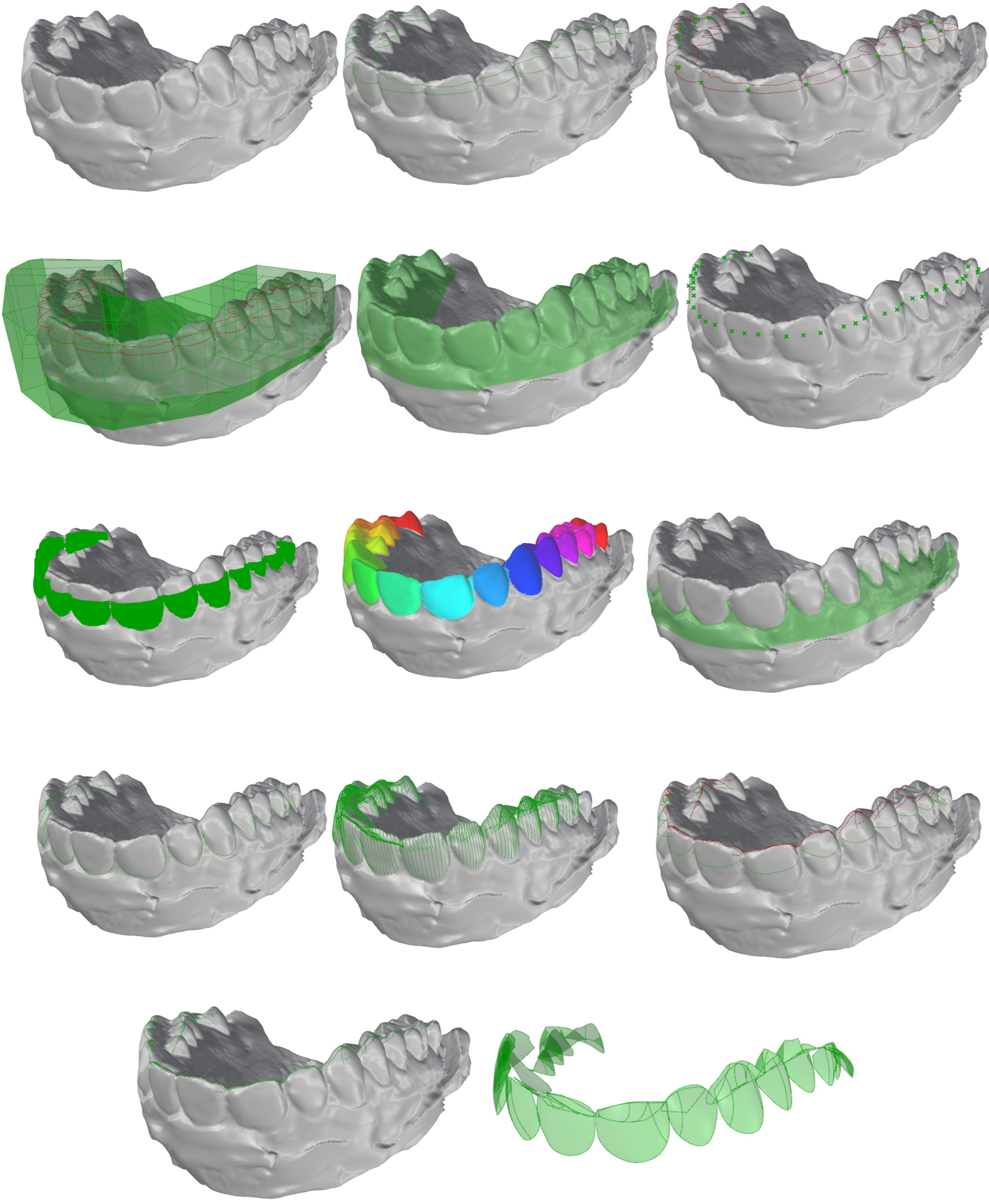


Figure 90. Complete overview of an example dental cast being processed: interdental finding, quick segmentation, gum line finding, custp finding, and surface generation.

12. Production detailing

Major manufacturing obstacles are discussed and shown to be surmountable, including thermoforming and the related bristling issues, increased actuation through modified surface structure, and the processing of the FDM prints using vapour solvents. Selections are made regarding materials, bristle lengths, and other important geometric factors.

While the FDM/thermoforming combination has been shown to be a promising manufacturing technology, several manufacturing decisions still need to be verified and optimised before it can be implemented as a manufacturing technique.

The main topics that need to be addressed are the consequences of thermoforming bristled TPE material into a complex concave arch, actuating the traditionally more rigid FDM, and finishing the product to a cohesive and food-safe whole.

12.1. Bristle sheet thermoforming

Thermoforming is traditionally relatively difficult to control, with variations in thickness and material distribution being highly dependent on the geometry of the mould.

The FDM surface underlying the thermoformed sheet eliminates part of this problem by providing a consistent and controlable thickness throughout the mouthpiece. Nonetheless, some inherent problems of thermoforming remain to be solved.

12.1.1. Stretching and distribution

During thermoforming, the sheet material is pulled straight down onto the mould, and freezes in place almost immediately. This means that, in places where the mould is highly vertical, the sheet is highly stretched, while it remains more solid on horizontal surfaces.

Unfortunately, this effect has bearing on the distribution of bristles along the sheet: when the material is stretched more, the bristles are spaced out along the surface of the mould.

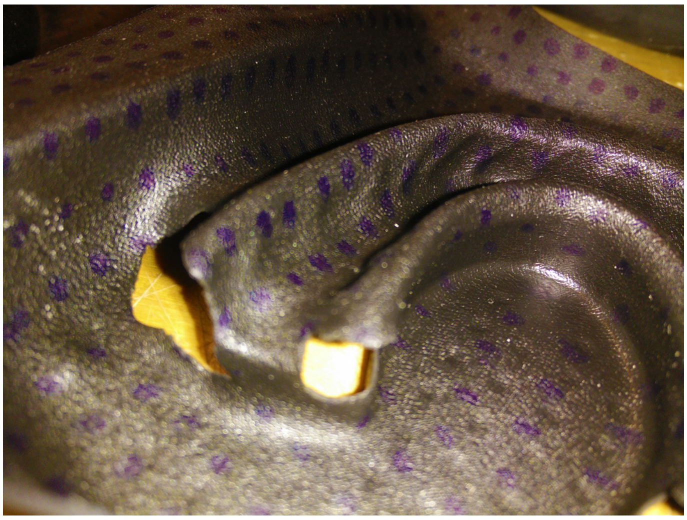


Figure 91. Stretching evenly spaced marks during TPE thermoforming

Thermoforming manufacturers use two main methods to combat this effect: multi-stage thermoforming, and mould alignment. The first method involves pre-forming the material using a more gentle mould, so that it can be formed more accurately later. The second method involves raising the resting surface around the mould so that the material is free to be 'drawn' into the cavities.

Both measures can be easily and cheaply implemented in the thermoforming process: neither feature needs to be custom-printed for every mouthpiece, as they only need to align with the rough dental arch or outer border, respectively.

Figure 93. Multi-stage thermoforming on an aligned mould results in much gentler deformations.

12.1.2. Bristle angling

Unlike other manufacturing methods, where the bristles are produced directly and with complete geometric freedom, the bristles made using thermoforming are always perpendicular to the surface of the mould. This is particularly inconvenient around the interdental regions. Because those regions are very small, but with a very high curvature, the bristles are always likely to point *away* from the interdental region. While around the gumline, design of the surface is essentially 'free', the interdental regions are constrained by the teeth.

This problem can be solved by introducing a lens-like area on the mould surface which centres around the desired region. As long as the width of this region is greater than the spacing between two tufts, at least one tuft is guaranteed to be aimed towards the interdental region.

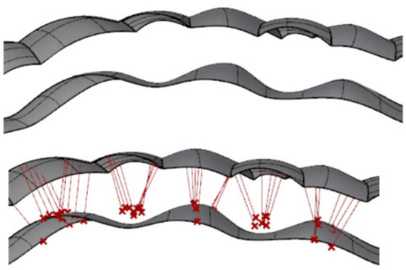


Figure 92. Perpendicular bristles aimed towards interdental regions using 'lens areas'

The obvious downside of this solution is that the surfaces themselves are further removed from the target surface. Consequently, the mouthpiece would need to actuate and deform further during every cycle to compensate for this distance.

This is yet another reason that bristle density should be optimised as far as possible: the more bristles there are, the more closely the sheet can adapt to the shape of the teeth.

12.1.3. Bristle length

The length of the bristles has an important effect on two counts: longer bristles 'splay' more easily, allowing a single tuft to cover and clean a relatively wide area on the tooth. The higher flexibility of a longer nylon wire also means that the local pressure on the tooth or gum is reduced, which in turn decreases the chance of gingival recession and enamel damage.

Unfortunately, as discussed in chapter 11, longer bristles mean that the surface should be offset further from the teeth themselves, reducing the dimensional accuracy of interdental surface sections.

Optimising this distance, therefore, depends on finding the highest distance from which interdental surfaces are still effective.

Using a basic range of bristle lengths, a number of mouthpieces can be tested using a simplified

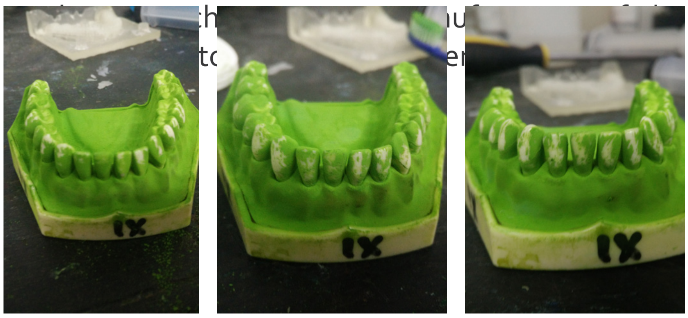


Figure 94. FDM contact for 1mm, 3mm, and 5mm bristles, respectively.

Though these factors are highly dependent on material, form, and a thousand other factors, 3 and 5mm appear to perform roughly equally on this model. For this reason, and to minimise size, 3mm bristles are used for the purposes of this project.

12.2. Actuation

The inflation mtotion of the mouthpiece has not been the focus of much attention so far, but must nevertheless be carefully considered. The new manufacturing technology both opens up some possibilities for controlling the airflow and deformation of the mouthpiece, and introduces some additional difficulties.

12.2.1. Surface flexibility

FDM materials are typically more rigid than those of traditional soft robotics manufacturing techniques. Very soft materials are not very well suited to being extruded, and tend to lead to reduced printing speeds and dimensional inaccuracies.

Fortunately, the control granted by FDM manufacturing can be applied to improve the surface flexibility. The surface does not need to be airtight, and can therefore be 'meshed' without repercussions.

Expansion under pressure is irrelevant parallel to the dental arch: the surface only needs to expand towards the teeth. Therefore, using an FDM mesh which consists mostly of threads running along the dental arch, sparsely interconnected using transversal threads, provides a structure which supports this type of deformation.

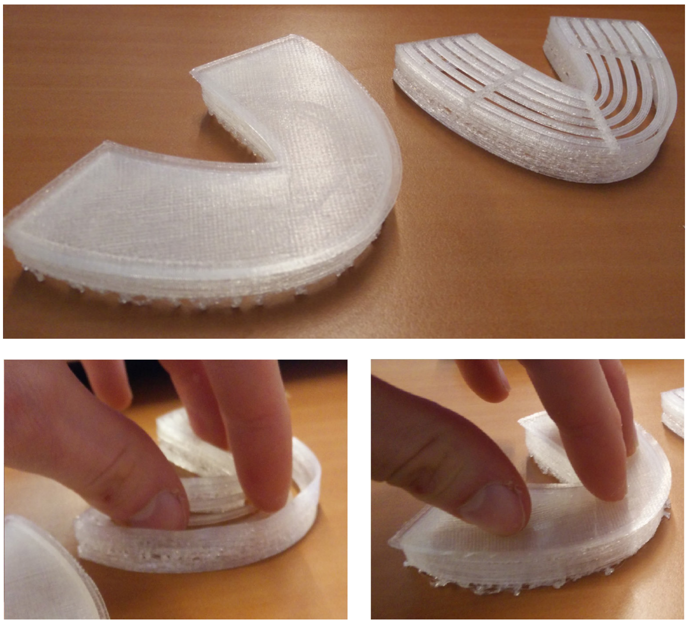


Figure 95. Solid shore A85 surface compared to a meshed counterpart under comparable force.

12.2.2. Local flexibility

The same principle can also be leveraged to relieve some of the problems that limit the expansion of the standard mouthpiece, as described in chapter 6: high-curvature areas and places where the flexible membrane connects to the rigid frame.

By decreasing the density of the frame around areas where the material connects to rigid sections of the system, and where curvature is unusually high, the whole mouthpiece should be able to move more freely without losing structural integrity.

Figure 96. Disconnected edges improve flexibility.

12.2.3. Air chamber size

The smaller the size of the air chamber in the mouthpiece, the less volume the pump needs to displace to create a certain pressure. For this reason, the standard mouthpiece is modeled with no distance between the frame and the actuator.

In the case of a frame which is printed entirely out of a single material, this is not an option. The smoothing step described in 12.3.2. would bond the two surfaces together, resulting in a solid TPE block.

Using a funnel-shaped dual-walled test design, it is possible to test how far the two walls need to be separated for them not to bond together.

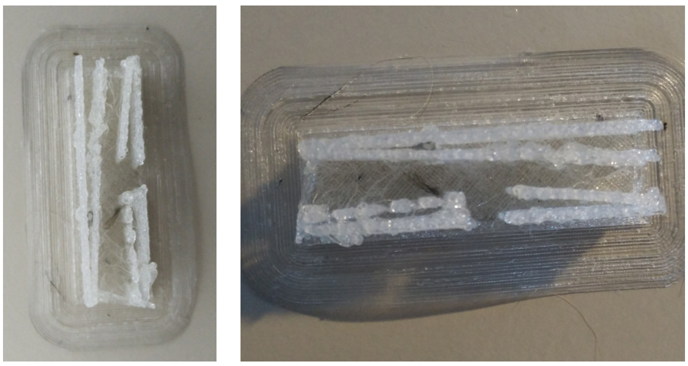


Figure 97. Material coalescing under the effects of solvent vapour. Walls have fused at distances below about .8mm

12.3. FDM processing

FDM printing was selected as a manufacturing method mostly because of the associated costs, and due to the availability of elastic materials. Unfortunately, it also comes with its own unique challenges.

12.3.1. Material selection & supports
The FDM material selection for this project is rather expansive, and can be found in its entirety in the appendix, section 12. The result of this exploration is the use of wet food-grade shore 95A polyether TPU.

Two filament types are commonly used for soluble support structures: polyvinyl alcohol, and high-impact polystyrene. The former dissolves in water, the latter in D-limonene. Both, however, take a relatively long time to do so: the methods are likely to add up to 24 hours to the manufacturing process.

With its lower price and higher processing temperature, HIPS seems more suitable for combining with TPU printing (which typically happens around 240 degrees).

12.3.2. TPU biocompatibility
Thermoplastic polyurethanes are the most solvent weldable and widely available TPEs, making them perfect for the intended application. Polyurethanes, however, are not commonly known for their biocompatibility. Fortunately, some TPUs (especially polyether-based TPUs) have been developed specifically for biomedical applications and have been found to be more biocompatible even than polypropylenes (Vogels et al., 2017).

12.3.3. Surface processing & adhesion
Bonding and surface treatment can both be solved in a single stoke using one of two techniques: sealant dipping, or vapour solvent welding/smoothing. The latter has the advantage of not adding an additional material,which may change the flexibility of the overall product. It does, however, need to be controlled carefully in order to preserve dimensional accuracy.

TPUs have varying solubility depending on their chemical makeup. Neither of the TPUs available for FDM prototyping process well using acetone or MEK, two relatively commonly used solvents.

Subsequent tests are based on a reference sheet kindly provided by a representative of Lubrizol (see appendix section 12), demonstrating the effectivenes of various solvents on an aliphatic polyether TPU. Application of chloroform and dimethylformamide yields the results shown in figure 100.

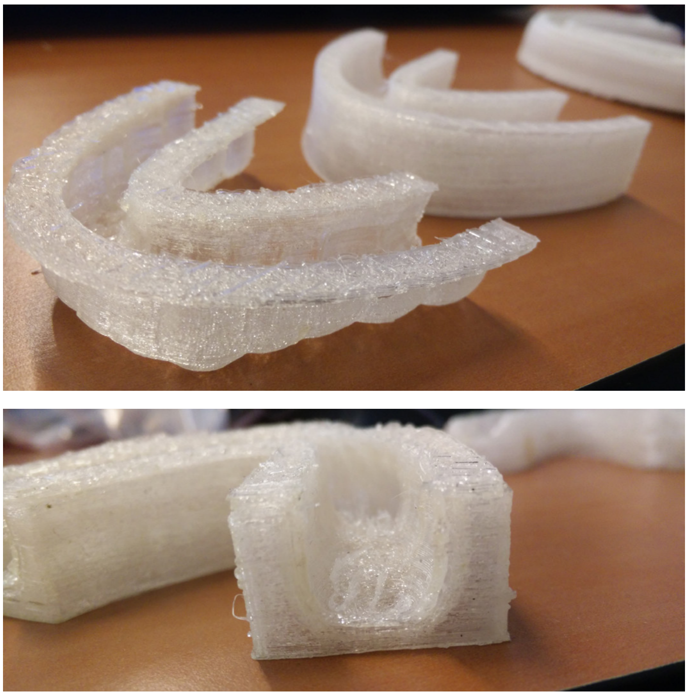


Figure 98. A snug-fitting TPU sheet and frame adhered using DMF solvent welding.

For this TPU, DMF is the more effective solvent by far. The sheet is affixed firmly and appears air-tight at low pressures.

The smoothing effects of the solvents are not immediately apparent in photographs due to the translucent material (which shows the untreated internal structures of the print). Tactile feedback, however, reveals that the surface irregularities are reduced significantly.

Based on these evaluations, it seems defensible that all major manufacturing uncertainties can be overcome using the aforementioned techniques. Flexible frame manufacture, bristle deformation, and assembly are all shown to be viable.

12.4. Final Prototype

The final prototype consists of as many aspects of the manufactured mouthpiece as can be implemented on short notice. The purpose of this prototype is to provide a frame of reference for the appearance and size of the mouthpiece, to validate the manufacturability of the individual components and their assembly, and to perform preliminary dental contact tests.

Note that previous tests by Dental Robotics have demonstrated that minute changes in geometry, flexibility and any one of an immeasurable number of parameters can dramatically alter the performance of a particular mouthpiece. As such, the tests of this mouthpiece are to be considered only qualitatively as a demonstration of principle rather than as a quantitative evaluation of efficacy.

12.4.1. Prototype design

The frame of the mouthpiece is designed as a 3mm offset based on the Frasaco model. Surfaces are knitted together using a 1.2mm-wide interdental section curved according to the principle demonstrated in 12.1.2. The outer walls of the frame are curved with a thickness of 2mm to improve rigidity.

Both flexible membranes are supported using a weave of 1mm TPE 'wires', which are modeled as intersections between the base polysurface and surfaces branching out from a central curve. A 1mm connecting 'bridge' between the weave and the outer wall covers the outside of the model.

Figure 99. Mesh built from 'wires' parallel to the dental arch

Both sheets are executed as pre-formed sheets to prevent interference from unpredictable thermoforming effects. Tapered 3x1mm bristles are extruded at 1.5mm intervals across the surface, perpendicular to its origins.

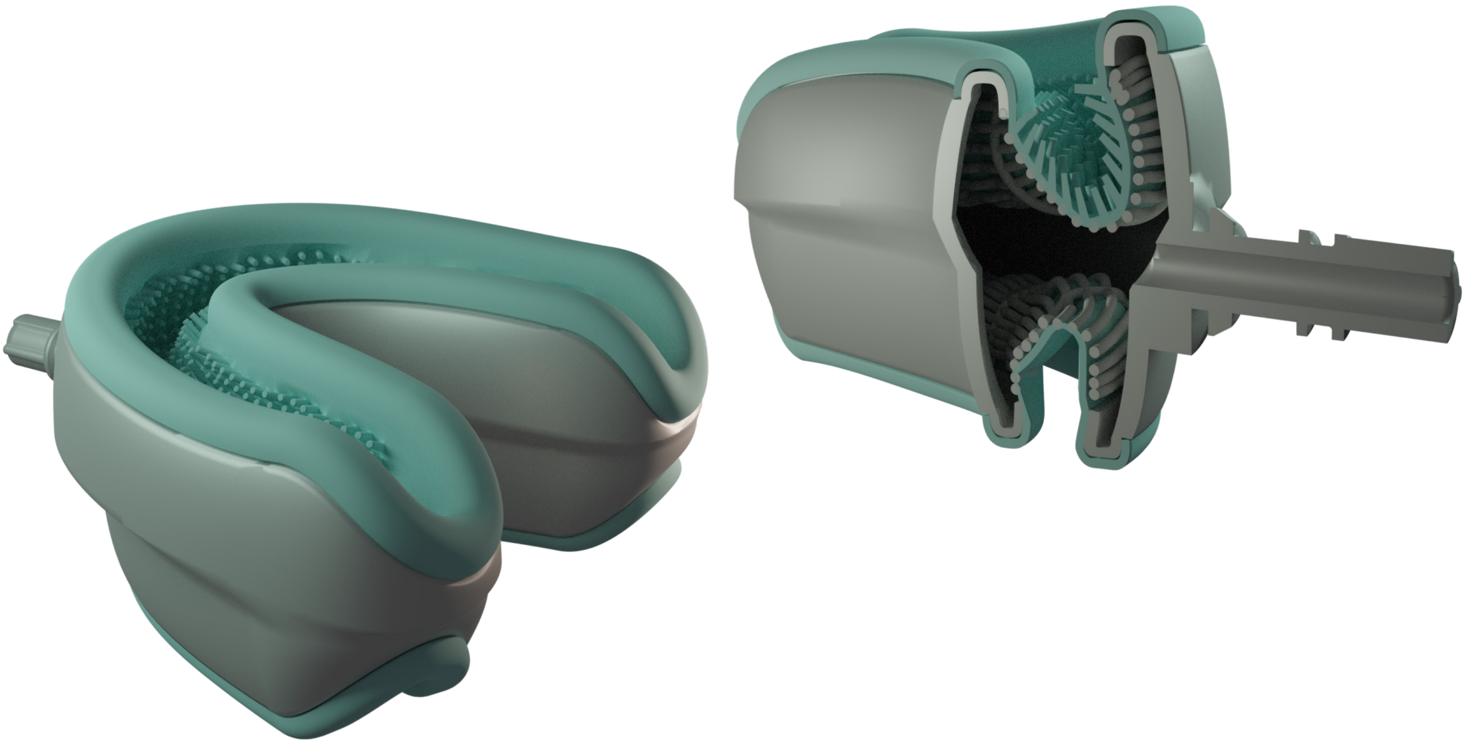


Figure 100. Overview and cross section of the prototyping model.

The design of the mouthpiece is based on an exploration of form and colour which can be found in the appendix, section 12.**4.**

12.4.2. Manufacturing & assembly

Manufacturing was unfortunately preceded by a dramatic defect in the only dual-extruder printer available, in which it has been... suggested that I played a minor part. As such, the frame is split in two to allow for the removal of internal support without HIPS structures. Prints are executed in a shore D40 TPE, with 0.8mm shelling, 20% infill, and printed at 60mm/s using a very uncooperative Anet A8 printer.

Both segments are adhered together before being post-processed using manually applied DMF.

Both sheets are cast from silicone, using a two-part mould printed using a FormLabs SLA printer at a resolution of 100 µm. Bristles were post-processed using a .8mm drill bit to guarantee manufacturability. The resulting sheets are adhered to the sheet by placing them on either side and applying suction to the inlet until the adhesive has cured.

12.4.3. Testing

Following a structural defect in the maxillary sheet, it was only possible to test the actuation of the mandibular half--which promptly burst after a single round of testing, further reinforcing the decision *not* to use silicone-cast bristle sheets for the purposes of this product.

Consequently, the test results shown in figure 101 only display the 'passive' performance of the maxilla, and the 'active' performance of the mandible. Because numerical evaluation is both time-intensive and not particularly useful, the evaluation is kept qualitative for the purposes of this report. For the full photographs, see the appendix, section 12.4.

The mouthpiece appears to perform relatively well interdentally, near the molars, and on teeth which are less exposed: exactly where the traditional mouthpiece underperforms. That being said, the overall performance of the mouthpiece is predictably not much better than that of the heavily optimised traditional mouthpiece. Gum line performance is also not visibly improved.

Figure 102. Prototype.

Figure 101. Comparison of normal mouthpiece contact and custom mouthpiece contact.

13. Costs & Development

Further development of the mouthpiece before the start of manufacturing is projected over a 6-month timeline. Based on material prices and processing time estimations, the production of a single mouthpiece should cost in the region of 3.5 euros.

While the concept is sufficiently developed for prototyping, several aspects will require refinement before the product is ready for mass manufacture. Table [] shows a schedule of these future developments, distributed over six months as stipulated in the product requirements.

13.1. Projected roadmap

A first priority is to investigate whether actuation is strictly necessary for the performance of the mouthpiece. As stipulated in earlier chapters, the utility of the mouthpiece's motion is reduced by the fact that the bristles are already touching the teeth before actuation. If comparable cleaning performance can be achieved without motion, the mouthpiece might be sold as a stand-alone product, removing the handle from the equation.

Regardless of the results, in vitro tests need to be validated using in vivo tests to confirm whether the improved contact of the mouthpiece corresponds with an improvement in plaque removal, and to optimise the product form for comfort and efficacy.

Simultaneously, the dental segmentation and geometry algorithm need to be improved--most likely using an existing external segmentation algorithm--to the point where the algorithm provides consistent results within the minimum range of dental arch dimensions and pathologies.

Following the evaluation of the manufacturing method, it becomes possible to choose the material. Several materials will probably need to be tested before an appropriate TPU is found that satisfies the expectations for extrusion, FDM manufacture, DMF smoothing and assembly, and food safety.

Once the in vivo validation has been completed, all the necessary material should be available to recruit dentists as partners. This is unlikely to be a major obstacle--a number of dentists have already expressed an interest in the programme.

After these steps, the manufacturing setup can be ramped up. Due to its dependency on relatively simple machinery, this should be easily scalable to the order of volumes over time.

Month number	1	2	3	4	5	6
Validation	Alternative actuation exploration	In vivo effectiveness validation			Generator consistency/ range	Test sequence
Automation	Dental segmentation refinement		Geometry generation refinement			
Manufacturing		Material test - extrusion	Material test - printing / processing	Material test - thermoforming	Manufacturing setup	
Distribution			Dentist partner program	Partner acquisition	Partner acquisition	Partner acquisition

Table 06. Projected post-graduation mouthpiece development.

13.2. Estimated product costs

The following is a summary of the estimated manufacturing times and costs. Material prices are based on bulk material costs and the estimated costs of any additional pre-processing (such as filament extrusion).

Labour costs are expressed as the human labour time multiplied by 30 euros. Investment costs cover machinery acquisition, based on an amount of comparable popular small-scale equipment.

Solvents are estimated to be applied across the surface at a .5mm thickness, or in the case of support solvent, to reach saturation at 50% mass.

Costs of the impression and shipping are considered external, and are not included in the consumer price multiplier, which for the purposes of this estimation is set at 4x.

Note that these calculations do not include development wages or research costs, meaning that the resulting figures are most likely an underestimate.

Machinery costs are estimates based on the costs of commonly used mid-end equipment (dental lab scanners, dual extrusion FDM printers, thermoforming equipment, vacuum chambers, and fume cupboards). Sheet manufacture costs are variable depending on the selected bristle material.

At a total variable manufacturing cost of 3.53 euros, the final consumer price should be around 15 euros per mouthpiece: if accurate, this falls neatly within the product requirements.

Step	Material price	Processing time	Labour costs	Machinery
First model				
Dental Impression	27.63 (2018 rates) + 3.6 (shipping)	2-3 days	-	-
Impression scan	-	3 min.	1.5	6,000
Scan processing	-	5 min.	3	-
Model validation/ correction	-	5 min.	3	-
Total	**31.2**	**2-3 days**	**7.5**	**6,000**
Repeat orders				
Frame manufacture	0.3 (TPU) + 0.2 (HIPS)	5 h.	.5	10 x 500
Frame processing	0.3 (D-limonene)	12 h.	.2	200
Sheet manufacture	0.1 (TPU) or 0.4 (Nylon)	.5 min.	.25	5,000-10,000
Sheet thermoforming	-	2 min.	.5	2,000
Assembly	0.05 (DMF)	12 h.	.5	2,000
Packaging/ shipping	.3 + 3.6	2-3 days	.13	-
Total	**1.25 + 3.9**	**3-4 days**	**2.28**	**15,000 - 20,000**

Table 07. Projected mouthpiece material costs, processing time, labour costs, and machinery investments.

14. Conclusion

For the extent of this project, it has been shown that the proposed manufacturing technology is effective, producable, and economically viable. Future development by Dental Robotics will still need to address uncertainties about user interaction, user comfort, and a variety of optimisations.

The project brief describes the three main goals of this project in three sections. The product should be shown to be effective, producable, and viable. This chapter discusses whether these goals has been achieved.

Note that some of the conclusions drawn from this project are qualitative and even subjective in nature: validation of the findings using a more rigourous approach is vital before long-term commitments are started.

14.1. Efficacy

It has been shown that an approximation of the proposed assembly can effectively clean a standard dental model, and appears to perform better than the standard mouthpiece in most of the problem areas stipulated in the design brief--with the exception of the gum lines.

How much of its efficacy is derived from the implemented actuation principles, however, compared to the simple fact that the bristles are aligned with the teeth themselves, is difficult to say.

14.2. Producability

Producability has been demonstrated to be possible, both in general and within the monetary and development constraints of the project. Automatic processing of dental meshes, with minor adjustments, is sufficiently accurate to generate a personalised mouthpiece. FDM manufacturing with dissolvable support structures and meshed flexible surfaces allows the mouthpiece to expand and contract sufficiently. DFM-based solvent welding results in a smooth and air-tight finished assembly.

While these steps have not yet been combined in a complete prototype, every single step has been shown to be viable. Combining the steps is not expected to introduce unexpected difficulties.

Figure 103. TPE-bristled product render.

14.3. Viability

Because of the size of this project, the focus leaned heavily towards manufacturing. While some research was performed on client context, and the product requirements were adjusted accordingly, the interest from the client side is difficult to gauge directly due to the secretive nature of the project. Extrapolating from the popularity of comparable projects, however, indicates that the mouthpiece outperforms alternatives in terms of price and level of personalisation.

14.4. Project Limitations

While the manufacturability of a custom mouthpiece has been fairly fully developed, consumer acceptance of the product has not yet been validated. The current size of the mouthpiece aids in its efficacy, but this is also likely results in it being less comfortable to use.

Similarly, the price point, surface form, and even general design were all create from a manufacturing and performance point of view. It would be worth Dental Robotics' while to review the design from a more user-centred perspective and make adjustments where necessary.

The design was created to conform as much as possible with the requirements outlined in chapter 7, but not all of these could be validated for obvious reasons. Since the product may well be faced with a relatively large number of users with pathological or unusual anatomies, it is important to check that the mouthpiece can indeed handle hypodontia, crowding, and similar afflictions.

15. References

3M (2017). Orthodontic product catalog. Retrieved on 04/02/2019 from https://multimedia.3m.com/mws/media/636611O/3m-orthodontic-product-catalog.pdf

Amabrush (N.D.). The Starter Sets. Retrieved on 30/01/2019 from https://www.amabrush.com/pages/starter-sets

Amabrush (N.D.). Antimicrobial Mouthpiece. Retrieved on 30/01/2019 from https://www.amabrush.com/products/mouthpiece

Amabrush (2018). The Amabrush Basic Starter Kit. Retrieved on 30/01/2019 from https://www.amabrush.com/products/starter-set-basic

American Artifacts (1998). Dr. Scott's Quack Electric Devices. Retrieved on 30/01/2019 from http://www.americanartifacts.com/smma/scott/scott.htm

Blizzident (2013). 3D Brush Payment. Retrieved on 30/01/2019 from http://www.blizzident.com/3d-brush-payment.html

Byrne, O. et al. (2018). Additive manufacturing of composite soft pneumatic actuators. Soft Robotics 5(6) doi:10.1089/soro.2018.0030

Chiiz (2017). Chiiz: Toothbrush 4.0 Retrieved on 04/02/2019 from https://www.kickstarter.com/projects/chiizfamily/chiiz-toothbrush-40

Chussid (N.D.). Absnormalities of the Teeth. Retrieved on 04/02/2019 from http://www.columbia.edu/itc/hs/dental/d7710/client_edit/dental_anomalies.pdf

ColorFabb (2019). NT Ninjaflex Midnight. Retrieved on 29/03/2019 from https://colorfabb.com/nt-ninjaflex-midnight

Connoly et al. (2017). Automatic design of fiber-reinforced soft actuators for trajectory matching. Proc Natl Acad Sci USA 114(1) pp51-56.

Covestro (2015). Thermoplastic polyurethane bonding. Retrieved on 26/02/2019 from https://www.tpu.covestro.com/en/Technologies/Processing/Machining-and-fabrication/Bonding

Dalidjan et al. (1995). Prediction of dental arch development: An assessment of Pont's index in three human populations. American Journal of Orthodontics and Dentofacial Orthopedics 107(5). pp465-475. https://doi.org/10.1016/S0889-5409(95)70113-3

Dentistry IQ (2017). Philips, Oral-B, Waterpik continue to dominate online sales of electric oral health appliances. Retrieved on 02/04/2019 from https://www.dentistryiq.com/articles/2017/03/philips-oral-b-waterpik-continue-to-dominate-electric-oral-healrh-appliance-market.html

Dmitrienko, S.V., Domenyuk, D.A., Kochkonyan, A.S., Karslieva, A.G., Dmitrienko, D.S. (2014). Interrelation between sagittal and transversal sizes in form variations of maxillary dental arches. Archiv Euromedica 4(2), pp10-13.

Dodson, T. B., & Susarla, S. M. (2010). Impacted wisdom teeth. BMJ clinical evidence, 2010, 1302.

Ekblad, A. (2018). Chiiz - Sonic-powered Automatic Toothbrush. Retrieved on 04/02/2019 from https://www.gismoreview.com/chiiz-toothbrush/

Emmi (2017). Emmi-dent Platinum Carbon Edition. Retrieved on 25/04/2019 from https://www.emmi-dent.com/ultrasonic-toothbrushes/platinum-models/15/platinum-carbon-edition?c=14

Fennek Drives (2018.1). Cheetah. Retrieved on 02/04/2019 from https://ninjatek.com/cheetah/

Fennek Drives (2018.2). Ninjaflex. Retrieved on 02/04/2019 from https://ninjatek.com/ninjaflex/

Ferraria et al. (1999). Three-dimensional dental arch curvature in human adolescents and adults. American Journal of Orthodontics and Dentofacial Orthopedics 115(4), pp401-405. https://doi.org/10.1016/S0889-5406(99)70259-3

De Gallier (2017). Electric toothbrush sales soaring in Britain with one in three now using them. Retrieved on 02/04/2019 from https://www.express.co.uk/life-style/life/809168/electric-toothbrushes-popular-brits-teeth-whitening-selfies

Galloway, K. C., Polygerinos, P., Walsh, C. J. and Wood, R. J. (2013) Mechanically programmable bend radius for fiber-reinforced soft actuators. 16th International Conference on Advanced Robotics (ICAR), Montevideo, 2013, pp. 1-6. doi: 10.1109/ICAR.2013.6766586

Gorden, L. & Tawichai, T. (2015). Electric toothbrushes thive in developed markets. Retrieved on 02/04/2019 from https://blog.euromonitor.com/electric-toothbrushes-thrive-in-developed-markets/

Grames, E. (2018). TPU Filament - Explained and Compared. Retrieved on 2/04/2019 from https://all3dp.com/2/tpu-filament-explained-and-compared/

Haeseman, P., et al. (2003). Evidence for the occurence of gingival recession and non-carious cervical lesions as a consequence of traumatic toothbrushing. J Clin Peri 42(16), pp237-255. https://doi.org/10.1111/jcpe.12330

Hategan, S.I., et al. (2018). Powder and Powder-Free Intra-Oral Scanners: Digital Impression Accuracy. Prim Dent J. 7(2), pp40-43.

Haynes-Kershaw, M. (2007). Electric toothbrushes through the century. Retrieved on 30/01/2019 from https://www.timetoast.com/timelines/electric-toothbushes-through-the-century

Humble Co. (2019). Humble Brush. Retrieved on 02/04/2019 from https://thehumble.co/

iData (2016). Dental Impression Materials Market Analysis. Retrieved on 02/04/2019 from https://idataresearch.com/product/dental-impression-materials-market-analysis-united-states-2017-2023-medcore/

IPE (2018). Thermoplastic Extrusions. Retrieved on 02/04/2019 from https://www.ipeweb.com/index.php/products/thermoplastic-extrusions

Ireland, R. (2010). A Dictionary of Dentistry. Oxford University Press

Kampbell-Dollaghan, K. (2014). I brushed my teeth with the world's first bluetooth toothbrush. Retrieved on 30/01/02019 from https://gizmodo.com/i-brushed-my-teeth-with-the-worlds-first-bluetooth-toot-1612484768

Kim, S., & Choi, S. (2018). Automatic tooth segmentation of dental mesh using a transverse plane. In 2018 40th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC) (pp. 4122-4125). IEEE.

Lestrel, P.E., Takahashi, O., & Kanazawa, E. (2004). A quantitative approach for measuring crowding in the dental arch : Fourier descriptors. American Journal of Orthodontics and Dentofacial Orthopedics 125(6) pp716-725.
Liao, S. H., Liu, S. J., Zou, B. J., Ding, X., Liang, Y., & Huang, J. H. (2015). Automatic tooth segmentation of dental mesh based on harmonic fields. BioMed research international, 2015.

Lubrizol (2014). Solvent Absorption Tecoflex TPU. Provided directly by personnel.

Mac Murray, B.C. et al. (2015). Poroelastic foams for simple fabrication of complex soft robots. Adv Mat. 27(41) pp6334-6340

Manatt (2014). Electric Toothbrushes Battle it out Before NAD. Retrieved on 30/01/2019 from https://www.manatt.com/Insights/Newsletters/Advertising-Law/Electric-Toothbrushes-Battle-It-Out-Before-NAD

Marcus, S.E. et al. (1996). Tooth retention and tooth loss in the permanent Dentition of adults in the United States, 1988-1991. Journal of Dental Research 75(2) pp684-695. https://doi.org/10.1177/002203459607502S08

Mayer (N.D.) The first electric toothbrush, Broxodent. Retrieved on 30/01/2019 from http://doctor-mayer.com/the-first-electric-toothbrush-the-broxodent-2/

Mirani, L. (2015). A quarter of a million people use an app to brush their teeth. Retrieved on 02/04/2019 from https://qz.com/355985/a-quarter-of-a-million-people-use-an-app-to-brush-their-teeth/

Mosadegh, B. et al. (2013). Pneumatic networks for soft robotics that actuate rapidly. Advanced functional materials

Mosely, T. (1937). Electric Toothbrush. United States Patent 2196667. Retrieved on 30/01/2019 from http://www.freepatentsonline.com/2196667.html

Moumneh (N.D.). Signs and symptoms of periodontal disease. Retrieved on 04/02/2019 from http://moumnehpolyclinic.com/default.aspx?MenuId=12&ContentID=4

Muhamad, A.H. (2014). The curve of dental arch in normal occlusion. Open Science Journal of Clinical Medicine 3(2) pp47-54.

Mulrey, C.A., Dellerman, P.A., Ludwar, R.J., White, D.J, Wild, J.E. (1992). A comparison of the end-rounding of nylon bristles in commercial toothbrushes: Crest Complete and Oral-B. J Clin Dent 3(2), pp47-50. https://www.ncbi.nlm.nih.gov/pubmed/1524685

Neff, J. (2002). Spinbrush cost P&G a hefty $475 million. Retrieved on 30/01/2019 from https://adage.com/article/news/spinbrush-cost-p-g-a-hefty-475-million/52204/

Optimet (n.d.) DS 6000 Dental Desktop Scanner. Retrieved on 02/04/2019 from https://www.optimet.com/ds6000.php

Oral-B (2016). Stage Power elektrische tandenborstel kids. Retrieved on 30/01/2019 from https://www.oralb.nl/nl-nl/producten/elektrische-tandenborstels/oral-b-stage-power-kids-elektrische-tandenborstel-star-wars

Oral-B (2018). Oral-B Genius 9000. Retrieved on 04/02/2019 from https://www.oralb.co.uk/en-gb/products/electric-toothbrushes/oral-b-genius-9000-electric-rechargable-toothbrush-white

J. T. B. Overvelde, T. Kloek, J. J. A. D'haen, and K. Bertoldi. (2015) Amplifying the response of soft actuators by harnessing snap-through instabilities. Proceedings of the National Academic of Sciences of the United States of America, 2015.
Papagiannis, A. & Halazonetis, D.J. (2016). Shape variation and covariation of upper and lower dental arches of an orthodontic population. Euro J of Ortho 38(2) pp202-211.

Paranhos, L.R., et al. (2011). Dental arch morphology in normal occlusions. Braz J Oral Sci. 10(1) pp475-480

PSI (2019). Polyester vs. polyether: what's the difference? Retrieved on 02/04/2019 from https://psiurethanes.com/urethane-resources/polyester-vs-polyether-whats-the-difference/

Puttalingaiah, V.D. et al. (2014). Assessing the association of taurodontism with numeric dention anomalies in an adult central Indian population. Journal of natural science, biology, and medicine. 5. 429-33. 10.4103/0976-9668.136222.

Raith et al. (2017). Artificial Neural Networks as a powerful numerical tool to classify specific features of a tooth based on 3D scan data. Computers in biology and medicine, 80, pp65-76.

Rosema N.A.M., Hennequin-Hoenderdos N.L., Versteeg P.A., van Palenstein Helderman W.H., van der Velden U., van der Weijden G.A. (2013). Plaque-removing efficacy of new and used manual toothbrushes -- a professional brushing study. Int J Dent Hygiene 11 pp237-243. https://doi.org/10.1111/idh.12021

Rossi, V. (N.D.) History of the Toothbrush. Retrieved on 30/01/2019 from https://www.sutori.com/story/history-of-the-toothbrush--42PXAqH1Bx2uhryhUBmXgA7j

Sandholm, J.E., Jouhikainen, M.P., and Dillon, R.F. (2015). US 9770217B2: Dental variation tracking and prediction. Retrieved from https://patents.google.com/patent/US9770217B2/en

Saruttichart, T. et al. (2017). Effectiveness of a motionless ultrasonic toothbrush in reducing plaque and gingival inflammation in patients with fixed orthodontic appliances. Ang. Ort. 87(2) pp279-285, https://doi.org/10.2319/042516-334.1

Sinterit (2019). TPE. Retrieved on 29/03/2019 from https://www.sinterit.com/shop/products/tpe-fresh-powder-2-kg-4l

Skillbond (2019). 3Shape E1 Scanner. Retrieved on 02/04/209 from https://www.skillbond.com/laboratory/product.asp?P_ID=8237

Sonar, H. A., & Paik, J. (2016). Soft pneumatic actuator skin for vibrotactile feedback. Front. Robot. AI. https://doi.org/10.3389/frobt.2015.00038

SRT (N.D.). Pneunet. Retrieved on 05/02/2019 from https://softroboticstoolkit.com/book/pneunets-bending-actuator.

Statista (2019). Oral care 2019. Retrieved on 02/04/209 from https://www.statista.com/outlook/70060000/144/oral-care/netherlands

Stokes, C. (2017). Adult teeth models for learning tooth morphology. Retrieved on 04/02/2019 from https://www.thingiverse.com/thing:2443703

Ten Cate, J.M. (2006). Biofilms, a new approach to the microbiology of dental plaque. Ondontology, 94(1), pp1-9. https://doi.org/10.1007/s10266-006-0063-3

TePe (2018). GOOD. Retrieved on 02/04 from https://www.tepe.com/uk/about-tepe/sustainability/good/

UTech (2009). Bio-based polyether diols offer high quality and performance from DuPont. Retrieved on 02/04/2019 from https://utech-polyurethane.com/information/bio-based-polyether-diols-offer-high-quality-performance-dupont/

Vogels et al. (2017). Biocompatibility and biomechanical analysis of elastic TPU threads as a new suture material. PubMed. 105(1) PP99-106, https://www.ncbi.nlm.nih.gov/pubmed/26426703

Wędrychowska-Szulc, B., Janiszewska-Olszowska, J., Stepień, P. (2010). Overall and anterior Bolton ratio in Class I, II, and III orthodontic patients, European Journal of Orthodontics, 32(1) pp313–318, https://doi.org/10.1093/ejo/cjp114

Wu, K (2018). Walking/crawling soft robot. Retrieved on 05/02/2019 from https://www.instructables.com/id/Walking-Crawling-Soft-Robot/

Wu, K., Chen, L., Li, J., & Zhou, Y. (2014). Tooth segmentation on dental meshes using morphologic skeleton. Computers & Graphics, 38, 199-211.

Xiao, J., & Gao, Y. (2017). The manufacture of 3D printing of medical grade TPU. Prog Add Man. 2(3) pp117-123