18. Children as Superheroes: Designing Playful 3D-Printed Facemasks for Maxillofacial Disorders

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Abstract

The paper describes a Human-Centred Design approach to developing customised facemasks for the orthopaedic correction of Class III malocclusions in children. The effectiveness of facemask therapy critically depends on patient's compliance with the recommended wear time, possibly ranging between 14-24 hours a day, over a time span of at least 9 months. Commercial facemasks are unaesthetic, uncomfortable and cause irritations due to the direct contact of plastic on the skin (Stocker *et al.*, 2016).

The research project SuperPowerMe develops a custom-made facemask to make the impact of the therapeutic intervention more sustainable in a critical stage of the physical and psychological child development.

Differently from commercial facemasks, SuperPowerMe is composed of 3D-printable biocompatible materials which make the device comfortable and customisable. SuperPowerMe adopts a gamification approach (Birk *et al.*,2016): a smartphone application provides games of increasing challenge where a superhero avatar wearing a facemask akin to the one worn by the child gains power fighting against monsters and other characters.

An ergonomic customised prototype facemask has been developed and will be soon tested at the Careggi Hospital in Florence, Italy.

Keywords: *Class III malocclusions, Children, Experience Design, Gamified therapy, 3D printing, Wearables.*

18.1 Introduction

Class III malocclusion is a craniofacial deformity characterized by a concave profile that results from retrusion of the maxilla, prognathism of the mandible or a combination of the two.At the dental level this skeletal relationship reflects

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into the prominence of the lower arch relative to the upper arch, or the inversion of the anterior bite.

This type of malocclusion has to be treated in childhood ideally before age 10, to improve dental occlusion and facial aesthetics, as well as to reduce the need for orthognathic surgery.

Class III malocclusion is treated using facemasks consisting of frontal and mental pads made from acrylic, connected by a quadrangular metal framework or a single midline stainless steel rod. The pads are only available in standardized shapes and in two sizes. In order to apply a forward traction to the maxilla, elastics are attached from an intraoral anchorage system to a cross bar extending in front of the mouth.

The effectiveness of facemask therapy depends on patient's compliance with the recommended wear time, possibly ranging between 14-24 hours a day, over at least 9 months. Commercial facemasks are unaesthetic, uncomfortable and may cause skin irritations due to uneven pressure by the standard anchorage pads. In a survey assessing acceptability of orthodontic appliances, facemask was rated as the least acceptable device (Abu and Karajeh, 2013). Beside aesthetics, children often complain about facemask bulkiness and instability, which compromise the treatment.

The objective of the project is to develop a custom-made and playful facemask to make the impact of the therapeutic intervention more sustainable in a critical stage of the physical and psychological development of the child.

In the following we describe the concept design of the mask illustrating all components and motivations for the approach.

Later we introduce the initial steps taken in prototyping the facemask and the related challenges. In the last part we present the future steps of the project.

18.2 Concept Design

SuperPowerMe is an ongoing research project aiming at designing facemasks for the early treatment of Class III malocclusions in children. The project is being developed by a multidisciplinary team of orthodontist doctors, designers, and technology experts with the involvement of children affected by Class III malocclusion and their families.

The project developed a concept of an innovative augmented facemask for the orthopedic correction of this maxillofacial disorder in children with the objective to overcome the limitations of commercial facemasks (poor aesthetics, skin irritation, poor Ergonomics) and to improve the acceptance by the young patients.

Commercial facemasks to treat maxillofacial disorders are seldom accepted by children. The design is solely focused on the functionality of the device without paying attention to other aspects of the User Experience like the aesthetics, Ergonomics, and motivating factors which are fundamental to make the therapy effective. Moreover, commercial facemasks do not fit adequately the child's anatomy, and the plastic may cause skin irritations.

SuperPowerMe aims at developing a wearable device using 3D printed biocompatible materials and customised design. The facemask can take several forms and colours depending on the child's preferences. Its aesthetics is co-designed with the patients.

In order to improve the acceptability and collaboration of the patients, SuperPowerMe adopts a gamification approach. An interactive game for smartphone and tablet is connected to the facemask and can be played only when the mask is worn.

The game automatically starts as soon as the child wears the facemask. It is designed as a never-ending adventure story which evolves with increasing levels of difficulty and challenges. The hero protagonist of the game wears a facemask akin to the one worn by the child, to facilitate the identification with the avatar. Super powers can be gained in two ways: 1) playing the game; 2) wearing the facemask for a defined number of hours a day.

The facemask hosts temperature and pressure sensors to monitor wear time and effectiveness of the therapy. Data related to wear time and pressure on the chin are collected and stored in a dedicated docking station, and downloaded each time the mask is placed on the unit. The docking station has two functions: 1) to recharge the batteries, 2) to automatically send the data to the dentist who can remotely monitor the effectiveness of the therapy.

18.3 State of the Art

There are no existing commercial alternatives to the concept of SuperPowerMe, which integrate all the features of the project together. A number of competitors provide solutions which only partially address the inconveniences of the current devices.

TheraMon (www.english.thera-mon.com/) and Dentitrac (https://somnomed.com/au/dental/product-range/compliance-recording/) developed microsensors to monitor wear time of removable orthodontic appliances.

Pads of marketed facemasks are all made of hard acrylic (Fig. 18.1). Different 3D-printable materials are being comparatively tested in our research. Among them, MED610 (by Stratasys Ltd., U.S.A.) and Polyamide 11 and 12.

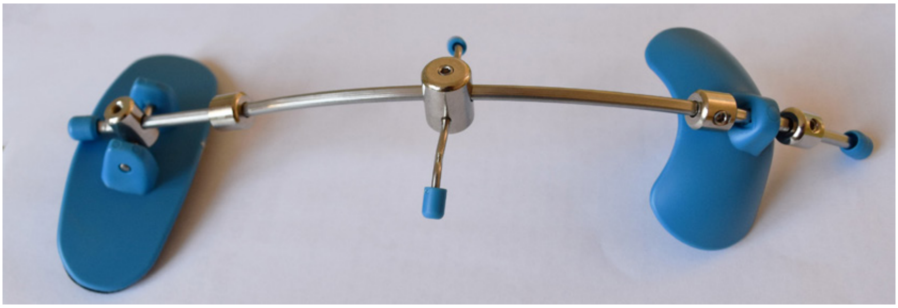

Fig. 18.1 - Commercial Petit Mask

These 3D-printable biocompatible materials have been used to custom-manufacture intraoral appliances for the treatment of sleep apnea (Vecchierini *et al.*, 2016). Polylactic acid is another biocompatible polymer that has been used in surgery and whose applicability in the production of customized facemasks deserves to be assessed (Wurm *et al.*, 2017). Additionally, 3D-printable silicones have been developed for the fabrication of facial prostheses and may be adequate to produce customized facemasks too (Jindal *et al.*, 2017).

The project experiments with many of the above mentioned materials to identify optimal solutions related to the improved wearability of the device.

Regarding the facemask customization, the majority of commercial custom devices concern 3D-printed maxillofacial implants and prosthesis. The application to facemasks for Class III malocclusion is unexplored.

The introduction of monitoring and gamification strategies into the management of facemask treatment is also highly original and innovative, there are no similar commercial products on the market.

18.4 Mask Design

After the concept design, a prototyping phase started involving a child suffering from a Class III malocclusion, with the aim to develop a customised facemask adapted to his anatomy. As explained in more detail below, a 3D model of the patient's face was realised and used as a basis to model the chin and front pads of the facemask so to reflect the patient's anatomy.

The 3D model was later used to design the central bar whose length should be calibrated/sized to allow him/her to freely move without impacting the throat, as often happens with commercial facemasks. Metal bars of commercial facemasks usually have to be cut by the doctor to avoid injuries on the neck/throat.

More in detail, the facemask design process developed along four main steps:

- 3D data acquisition and object reconstruction;
- 3D modeling and design;
- selection of materials;
- 3D printing.

The steps are described below.

18.4.1 3D Data Acquisition and Object Reconstruction

The patient's face 3D model was acquired using a photogrammetry station (Face Scanner Maxi 6, Polishape 3D, Bari, Italy). Photogrammetry is method that allows to create a 3D model starting from a series of photos which preserve both the original shape and dimensions. Once the photos were taken, the software Agisoft Metashape was used to process them and to create a 3D model of the patient's face. This phase of the process is crucial and delicate since the acquisition method requires the patient to remain still during the operation. The procedure is easily accomplished with adults, but it is not equally simple with young patients. If the patient moves during the acquisition, the procedure has to be repeated several times before obtaining a complete and accurate 3D model.

Once the model has been acquired, a final check has to be done to verify the full compliance and accuracy of the measurements of the 3D model with the child's face.

18.4.2 3D Modeling and Design

Once the child's face model was acquired, the software Blender was used to design the customised facemask. The 3D model of the patient's face was used as a physical reference to design the front and chin pads in order to obtain a model perfectly fitting the patient's anatomy. The next step was to connect the chin and front pads with a central bar, whose length was carefully adapted to the anatomy and length of the child's face. This bar was not conceived just as a way to connect the pads but it was modelled following the profile of the child's face so to provide a comfortable fit, and avoid sight problems to the child since the bar is placed between the eyes (Fig. 18.2).

The process was iterated several times before obtaining an adequate fit both in terms of Ergonomics and technology requirements.

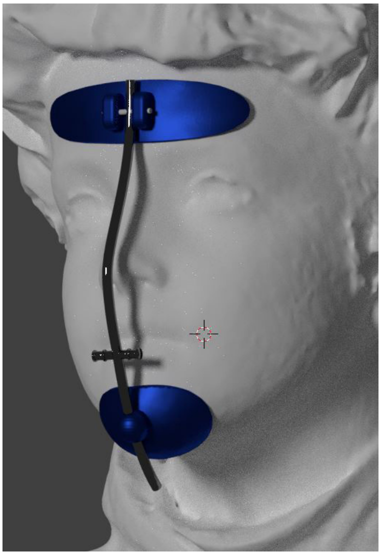

Fig. 18.2 - 3D model of the customised facemask

In fact, a digital facemask perfectly fitting the 3D model of the patient's face, may not result in a perfectly fitting of the 3D printed model. Therefore, the effort to optimize the process of modelling and printing was made in the experimental project.

18.4.3 Selection of Materials

A research on bio-compatible materials was conducted to identify the materials which could both avoid irritations on the skin and at the same time be flexible and robust to resist the traction of the elastic bands anchored to the intraoral anchorage system. Indeed, patients usually complain about the discomfort and abrasions caused by the daily use of commercial facemasks.

We oriented our research on materials with the following characteristics:

Biocompatibility: the facemask has to be worn for 14 hours per day, so it is absolutely necessary to avoid any negative impact on the patient's skin due to the prolonged exposure.

Suitability for 3D printing: the material can be 3D printed using one of the following techniques: fused deposition modeling (FDM), stereolithography (SLA), or selective laser sintering (SLS). FDM is an additive manufacturing process where an object is built by selectively depositing melted material in a pre-determined path layer-by-layer. The materials used for FDM are usually thermoplastic polymers and come in a filament form. In SLA, the object is created by selectively curing a polymer resin layer-by-layer using an ultraviolet laser beam. The materials used in SLA are usually photosensitive thermoset polymers that come in a liquid form. SLS is the process of creating objects from powders. The laser heats the powder fusing the particles in the powder together into a solid form.

Sturdiness: the material must be flexible and robust to resist the traction of the elastic bands anchored to the intraoral anchorage system.

The result of this research brought to identify the following candidates:

- Nylon PA12 an affordable, resistant and biocompatible material that can be printed FDM and SLA 3D printers;
- MED610, which is usually used in facemasks for the treatment of burns in children;
- Veroflex which is used for producing glasses;
- Nylon 12 with carbon fibers for the central bar. This material is particularly robust and can represent a good alternative to the metal which makes the central bar heavy to wear.

18.4.4 3D Printing

The first prototypes (Fig. 18.3) of the customised facemask were realised using an FDM Ultimaker 3. The orientation of the deposited layers was carefully considered to avoid any fragility of the structure.

Since the facemask has a long and thin shape, the traction of the elastic bands which anchor the mask to intraoral anchorage system can divide the filament layers and break down the central bar. To avoid this inconvenient, it was necessary to design the model so that the layers orientation was perpendicular to the elastic bands. This method proved to be successful.

18.5 Future Steps

The project has so far reached a maturity level to be turned in a clinical trial. This will be conducted at the Orthodontic Clinic of the Careggi University Hospital, Florence, (Italy) under the supervision of Prof. Franchi.

The clinical trial will compare the efficacy of the customized facemask versus the conventional facemask in pre-pubertal patients with Class III malocclusion. The trial will also assess patients' acceptability and compliance of the

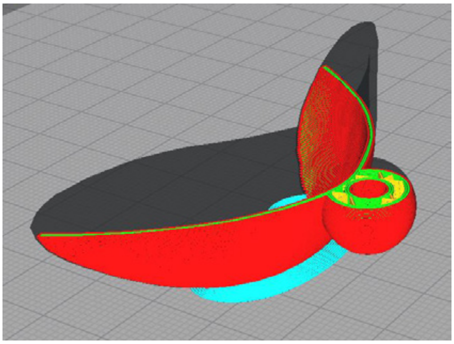

Fig. 18.3 - Detail of the chin support 3D model, ready to be printed

2 types of facemasks and also the occurrence of complications (skin and lip irritation, gingival recession).

Beside the evaluation of the efficacy of the facemask during the first trial, next steps of the project will regard the design and implementation of the embedded electronics, the development of the game and the creation of new designs to enrich the aesthetics of the facemask.

During the design phase, children with Class III malocclusion interviewed by the therapist, expressed the wish to personalise the facemask using for example the symbols of the favorite football team, or the favorite cartoon characters, or simply the most preferred colours. Very preliminary attempts to personalise the face masks and submit the design to the young patients' evaluations were accomplished in different phases of the design process. In some cases, feedback was collected from the patients themselves, in the majority of the cases from the therapists and the parents during interviews and participatory design activities. Children were generally reluctant to provide their feedback. Most likely their previous experience with current face masks made them suspicious and unable to imagine a playful way to use the mask. Interviewed parents were keen to collaborate, seeing the project as a concrete step ahead in the therapy. The therapists who are currently collaborating in the project are firmly convinced about the positive impact of the research for the quality of life of their patients.

Embedded electronics. A custom-made electronic board, equipped with sensors is currently being designed. It will allow to track and store data about temperature and pressure on the front and chin of the child in order to monitor the actual wear time of the facemask. A docking station will be also developed to allow to recharge the battery, store the data coming from the sensors and eventually send the data to the therapist.

Game design. A simulation of the video game has been also developed to be evaluated with young patients (Fig. 18.4). The game design started with a benchmark study articulated in the following steps.

- *Analysis of titles published a few years ago but still in vogue.* The purpose was to understand the characteristics that allowed them to be played assiduously for a long time, since our game is supposed to be played for several months to make the therapy effective. Examples of game included in this category are: 1) World of Warcraft, a PC-based MMORPG game (Massive Multiplayer Online Role-Playing Game) developed by Blizzard Entertainment in 2004. It is still very popular within a community of active of players, mostly driven by the competition. It is articulated on one single never ending plot where the player can create his avatar and take the challenge s/he like; 2) League of Legends, a MOBA game (Multiplayer Online Battle Arena) released in 2009 by Riot Games. Players can choose their avatar with unique abilities to combat is a closed arena. To win, both the skill of the individual player and group strategies are necessary; 3) Minecraft, a sandbox and survival game released in 2009 and created by a Swedish programmer Markus Persson, acquired by Microsoft in 2014. The player enters a virtually infinite and randomly generated world in which, besides to complete some basic missions, has to survive to hunger and enemy attacks.
- *Analysis of titles played for several hours a day:* Football games (eg FIFA), Multiplayer First-Person Shooters (e.g. the Counter Strike or Call of Duty), Management games (e.g. Simpsons), Role-playing games (e.g. Pokémon) and Racing games (e.g. Mario Kart) are all characterised by never ending plots and high competitiveness. An inspiring example is the Management Game "The Simpsons" released by Springfield. The game exploits a temporal factor: every activity, to be completed, requires a certain amount of coins and time to be accomplished. For example, the construction of a building requires a high number of coins and twelve hours to be completed. This concept proved to be useful for the purposes of our game: rather than involving a child in gaming for a long period of time during the day, the challenges can be divided into several daily sessions of a few minutes each to get closer to the objective.
- *Game-based App for smartphone to support behaviour change.* Examples include: 1) QuitNow! to quit smoking. The app sends an alert when an objective is reached and reminds about the related health improvements; 2) Zombies, Run! Aims to stimulate running. The player has to survive a zombie invasion running for a definite time. In both cases, time is a key factor of the game.

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- *Game-based app with medical / health purposes.* Examples include: 1) Philips Sonicare for Kids, a customizable electric toothbrush for children to use together with a game developed for smartphones and tablets where the child will have to help a pet to clean its teeth and defeat the bacteria of mouth; 2) Bayer DIDGET for Nintendo DS, a blood glucose meter produced by Bayer. The results of measurements are converted in points that can be spent during the game to unlock new levels and customizations.

From the benchmark analysis, the following features were selected for our game design: a single never-ending plot articulated in smaller stories to give the impression of improvement; interaction between virtual and real world through the use of objects (e.g. face mask) present in both; simple mechanics tailored to young patients; use of notifications to reward the player. We deliberately decided not to design a community-based game due to the young age of our target. The social aspect of the game was realised with notifications like: "Congratulations! You are ranked among the top ten players of the game!".

The main character of the plot is the elf Araton, the strongest among the forest's elves, who lives on the slopes of a giant tree together with other elves. The tree produces fruits which are the only source of food for the elves. These fruits are so delicious that the tree is constantly target of the attacks of evil creatures. Araton has a secret weapon, a face mask that allows him to run above the bark of the tree without ever getting tired and to throw waves of energy capable of destroying the enemy. The aim of the story is to guide the sympathetic avatar in climbing the tree and defeating the evil entities that infest it stealing the fruits.

The game has a vertical development where the elves have to jump from one leaf to another, destroying enemies so as to increase the overall score. Some of them will carry baskets containing some stolen fruits, which can be harvested once the enemies have been defeated.

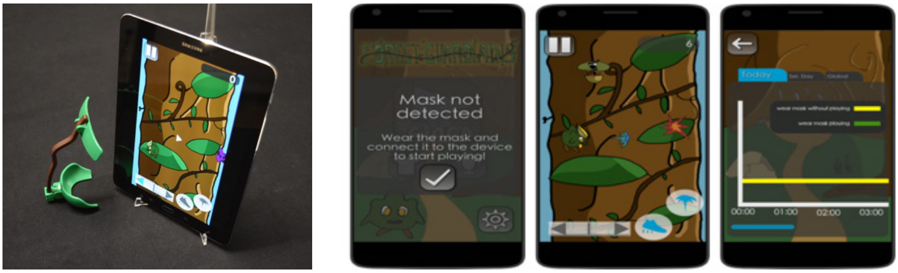

Fig. 18.4 - A simulation of the game associated to the facemask

The scoring system was designed according to the following rules:

- 1 point for each defeated enemy;
- 5 points for each fruit harvested;
- 5 points for every ten minutes of "passive" play, that is for the wearing time of the face mask during the day by the child without playing calculated by the embedded sensors.

The current version of the game provides real time feedback with motivational cues to stimulate the child in wearing the facemask. Personalized notifications and rewards (e.g. "Congratulations you have reached level four! You will get more power tonight while sleeping with your face mask mask") are provided during the game.

A prototype version of the game was successfully tested with three children who did not suffer from Class III malocclusion with the objective to evaluate basic dynamics and the overall concept. A further step will be necessary to involve young patients with Class III malocclusion to fully evaluate the prototype before starting the technical implementation.

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