International Journal on Interactive Design and Manufacturing (IJIDeM)
https://doi.org/10.1007/s12008-020-00743-z

SHORT ORIGINAL PAPER

# Concept selection and interactive design of an orthodontic functional appliance

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Received: 11 March 2020 / Accepted: 8 October 2020


**Abstract**
Demand for innovation represents a driver not only in the industrial field but also in niche markets such as orthodontics. Among different type of orthodontic devices, functional appliances are used for the correction of class II skeletal malocclusion, mostly in young patients. In a previous study based on a systematic design approach, several concepts were generated for this device. This work shortly introduces the concept selection and the interactive design process of the device. The concept consisting of two-side guiding surfaces, obtained by TRIZ inventive principles, has been selected by the decision matrix. This concept consists in guiding the jaw movements without any connections between the parts of the device. Operating on patient morphometrics parameters, the proposed approach allows to establish a virtual interaction during the design of the device by facilitating the collaboration between orthodontist, dental technician, designer and the software, through a dedicated user interface. Dedicated algorithms were also developed to simulate the occlusion correction and the mandible path, and to support the geometric modelling in a virtual environment. As a result, the proposed approach allows manufacturing patient-customized devices using a digital interactive workflow in an innovative way.

**Keywords** Orthodontics · Functional appliances · Concept selection · Morphometric parameters · Interactive design

## 1 Introduction

Orthodontic functional appliances are intraoral devices for correcting skeletal class II malocclusions where mandibular deficiencies are present, as defined by Angle [1]. The main purpose of these devices is mandibular repositioning, stimulating bone shape remodeling of the condylar process by enhancing upward and backward growth due to induced stress.

Usually, the design of these devices follows the "component approach" [1], where the most effective components,

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or simply the known ones, are selected, and the device is assembled by the dental technicians following the clinician guidelines and the patient's specifications.

Different classifications of functional appliance are described in the literature. One of the most useful refers to the advancement principles applied, i.e. the mechanisms. The most used mechanisms consist of sliding pins coupled with tubes, as in the Herbst appliance [1, 2], or of ramps, as in the Twin Block appliance [1]; both prevent the incorrect occlusion pattern by forcing the patient to move the mandible forward. These mechanisms can be utilized in both removable and fixed devices and this represents a second classification, based on patients' compliance [3].

Several issues can affect these devices [1, 2]. Size and shape can cause lack of patient's compliance and can generate sores in the mouth soft tissues; hygiene can be affected by plaque accumulation; moreover, positioning/removal procedures usually are difficult and/or hurting. A systematic analysis of these problems based on Quality Functional Deployment allowed defining new device concepts [4]. After the selection of the best concept, in this work, considering patient specific morphometric parameters, an innovative interactive design approach is proposed. Dedicated algorithms were also developed, allowing the production of customized devices.

## 2 Concept selection

### 2.1 Materials and methods

In the early phases of the device development [4], designers identified a set of customer requirements using tools such as the Quality Function Deployment (QFD) for collecting data. Then, designers generated several concepts answering to the requirements using systematic design, the morphological method and creativity enhancing methods like TRIZ [5].

After the conceptual design phase, evaluation and selection activities had to be accomplished. Among the concept selection methods, the designers opted for a structured one matching the approaches applied during the previous phases. This method, called decision matrix, or Pugh's method [6, 7], rates each concept against weighted selection criteria. This approach tests the completeness and understanding of each criterion, identifies rapidly the strongest alternatives and helps fostering new ones.

Basically, after a preliminary phase of go/no-go and feasibility consideration skim, the decision matrix is compiled. Concepts are described at the same level of abstraction and sketches are used for representing them. Criteria come from the most important customers' requirements. For each criterion, relative importance weights are imposed by the design team, elaborating customers' requirements in order to prioritize the criteria. The relative weights are expressed as percentages and their total is 100%. The evaluation considers a reference concept and scores the others using a three-number scale 1,0,1, where 0 means "the same", 1 if the concept is "better than" the reference and − 1 if the concept is "worse than" it. The concepts scoring better values are considered for further development; those with lower values can be discarded; the concepts in the middle can be reconsidered for some improvement.

### 2.2 Case study

Analyzing the sixteen requirements identified in the previous work using the QFD [4], four most important functions for the appliance functionality, i.e., the core of the device, were highlighted: correction of the mandible position, correction adjustment, human tissue protection and connection to ensure physiological movements (first column in Table 1). To satisfy these functions, several physical principles were identified using creative methods such as the Inventive principles from TRIZ as shown in Table 1. Then, combining a physical principle for each function by the morphological method, 9 concepts were generated. Table 2 shows 3 of the most promising concepts. Concept C1 consists of a single side mechanism. The main idea was to simplify the device, removing non needed parts. Concept C5 is a two-side solution with a surface in which a pin can slide to accomplish the correction smoothly. The surrounding idea was to reduce patient discomfort and device breakages. Concept C8 with a magnetic solution, follows TRIZ dynamization trend, increasing ideality. The main idea was to reduce the total volume of the device and avoid mechanism breakages.

Due to its level of diffusion, the development team considers the Herbst appliance as the reference product. The elaboration of the most important customers' requirements and engineering specifications allows identifying six selection criteria: simplicity, movements, invasiveness, hygiene, reliability and ideality. Simplicity refers to a bunch of requirements as easiness of use, number of pieces, mountability, etc. Movements refers to the mandible allowed movements. Invasiveness relates to the dimensions, appearance and comfort of the device. Hygiene refers to device cleaning time and maintenance. Reliability implies several notions regarding device efficiency and undesirable effects. Ideality refers directly to the TRIZ theory in terms of functions achievement by the system, absence of drawbacks, features existance etc. The weight assigned to each criterion is computed by taking into account the data elaborated during QFD activities; the percentages mirror the importance values found. For this reason, reliability has the highest value, 25%, while ideality has the lowest one, 5%. Table 3 reports the decision matrix as compiled by the design team.

**Table 1** Morphological matrix: functions and principles

| Functions | Principles | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| Mandible positioning | Obstacle | Guide | Force | Momentum | Magnetic attraction | Magnetic repulsion |
| Adjustment | Continuous | Discretized | Changeable structure | No adjustments | | |
| Human tissue protection | Surface and shape study | Cover tissues | Cover the appliance | Release healing substances | Position change | |
| Connection | Flexible linkage | No linkages | | | | |

**Table 2** The three best rated concepts with principles combination, sketch and main underlying idea highlighted

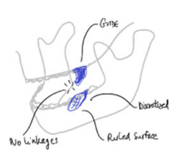
| Concept | Func./princ. | | | | Sketch | Comments |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | | |
| C1 | 2 | 3 | 5 | 2 |   | TRIZ:<br>Trend<br>(Simplicity-Complexity- Simplicity) |
| C2 | 2 | 1 | 5 | 1 | – | – |
| C3 | 1 | 3 | 5 | 1 | – | – |
| C4 | 1 | 2 | 5 | 1 | – | – |
| C5 | 2 | 2 | 3 | 2 |   | TRIZ<br>Inventive principles<br>(14 Spheroidality; 3 Local quality)<br>Working on surfaces |
| C6 | 2 | 2 | 3 | 1 | – | – |
| C7 | 1 | 1 | 5 | 1 | – | – |
| C8 | 6 | 4 | 3 | 2 |   | TRIZ:<br>Trend<br>(Increasing Dynamism)<br>Using magnetic force in repulsive arrangement |
| C9 | 2 | 3 | 3 | 2 | – | – |

**Table 3** Decision matrix

| Criteria | Weight (%) | Ref. (Herbst) | Concepts | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | C1 | C2 | C3 | C4 | C5 | C6 | C7 | C8 | C9 |
| Simplicity | 20 | 0 | 1 | – 1 | 1 | 0 | 1 | 0 | 0 | 1 | – 1 |
| Movements | 15 | 0 | 1 | 0 | 0 | 0 | 1 | 1 | 0 | 1 | 1 |
| Invasiveness | 20 | 0 | 1 | 0 | 0 | 0 | 0 | 0 | 0 | 1 | 0 |
| Hygiene | 15 | 0 | 1 | 0 | 0 | 1 | 1 | 0 | 0 | 1 | 0 |
| Reliability | 25 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 1 | 0 | 1 |
| Ideality | 5 | 0 | 0 | 0 | 1 | 0 | 1 | 1 | 1 | 1 | 1 |
| | 100 | | | | | | | | | | |
| Net score | | | 4 | – 1 | 2 | 1 | 5 | 2 | 2 | 5 | 2 |
| Weighted total | | | 70 | – 20 | 25 | 15 | 80 | 20 | 30 | 75 | 25 |

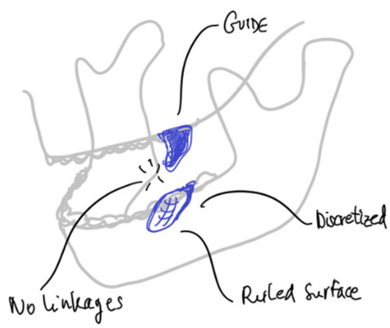



**Fig. 1** The selected concept solution (C5): guiding surfaces

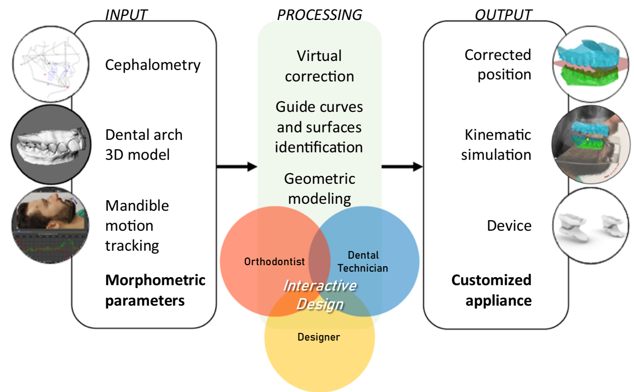



**Fig. 2** The interactive design approach

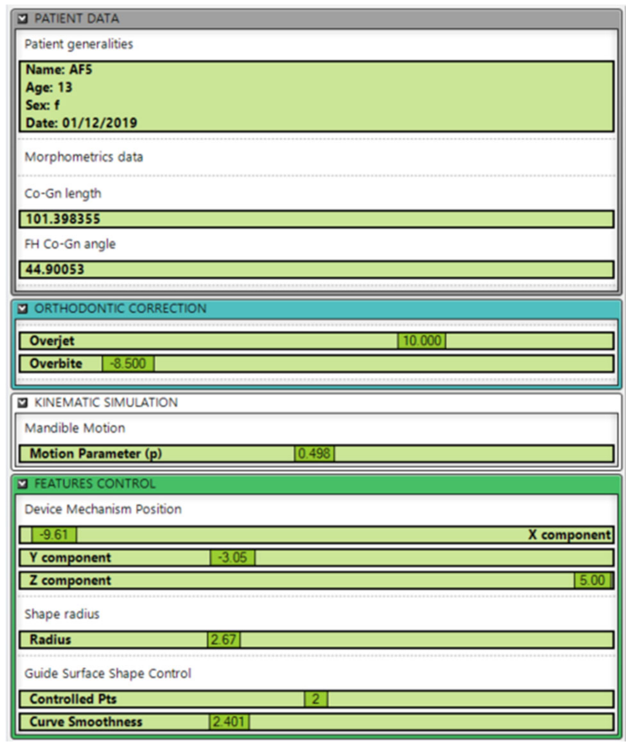



**Fig. 3** The dedicated user interface for interactive design

As an overall observation, every concept seems to be better than the Herbst appliance used as reference datum, except for C2 that relies on a pushing mechanism. This was somehow expected since actual appliance do not meet customers' requirements at all, as described in [4].

Average score, from 15 to 30, obtained by C3, C4, C6, C7 and C9, are reputed as "not good enough"; they would deserve further examination. Concept C1, with its 70-point score, is among the best, but it seems to have some operating weaknesses, respect to the others. Concepts C5 and C8 have the best scores with 80 and 75 values, respectively. Concept C8, based on a magnetic repulsion mechanism, appears more ideal but needs further investigations on biocompatibility and other issues related to magnetic interference with daily life objects. On the other hand, C5 shows less drawbacks than the others, especially regarding the patient's acceptance of the device. For these reasons, concept C5 (see Fig. 1) has been developed by an interactive design approach. The implementation of the selected solution is dealing with the morphometric data and the kinematics of the patients' mandibles, the modelling methodology, the complete design workflow and the simulation of the implemented correction.

## 3 Design approach

Interactive design is the practice of data exchange/processing between people and technology, mimicking human interactions [8, 9]. Based on the results of the selection phase, the guiding surfaces concept was developed by following the interactive design approach shown in Fig. 2.

The main idea is to establish an interaction during the design of the device by facilitating the collaboration between orthodontist, dental technician, designer and virtual model trough algorithms implemented in software, operating on morphometric data and manufacturing technologies, through a dedicated user interface (Fig. 3). Dedicated algorithms were developed in Grasshopper and Python in Rhinoceros V6 software to accomplish the various design activities for the concept selected.

The implementation of the selected concept adopts as input morphometric parameters measured on the patient x-ray images and cephalometry, dental casts and related 3D models of the dental arches, and opening-closing video sequence for the jaw motion tracking.

The collected data are introduced in a CAD software, where orthodontist and designer exploit the user interface in order to establish the correct occlusion, positioning the mandible using "Overjet" and "Overbite" sliders. Then the dedicated algorithm suggests the corrected occlusion path. Based on his/her experience, the orthodontist can modify

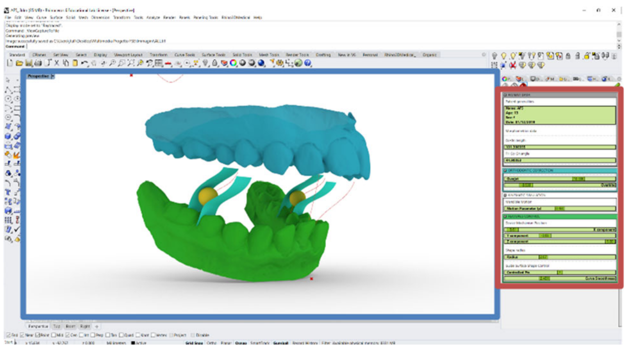


**Fig. 4** The instantaneous visual feedback in the 3D virtual workspace (in the center) during the interaction with the user interface (on the right side). It is shown the 3D scans in an open position: maxilla arch (blue), mandible arch corrected (green), the path curves (red) and the surfaces, geometric features of the selected concept (light green and yellow) (color figure online)

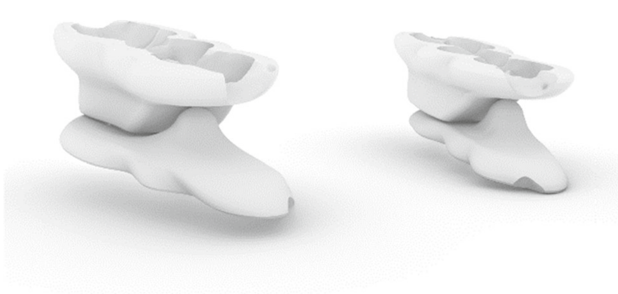


**Fig. 5** The 3D model of the device

this path using a specific user interface that gives an instantaneous visual feedback in the 3D virtual workspace (Fig. 4).

The core of the algorithm operates on the uncorrected path of the mandible. It generates the new corrected path of every point joined to the mandible, in particular incisal point and the pins center. It describes these paths using NURBS curves with 5 control points. The sliders in the user interface permit to shape the curve modifying the range of points that are affected by this operation (in Fig. 3 “Controlled Pts”) and the weight of each point (in Fig. 3 “Curve Smoothness”).

Then, the geometric features of the device, which ensure the planned path, are extracted and visualized. Moreover, as a result, it is possible to simulate the corrected mandibular movement. Considering the dental arch 3D model and the extracted features, the designer shapes customized device (Fig. 5) by a dedicated geometric modeling procedure.

Then, the appliance is manufactured by the dental technician by additive manufacturing technologies (Fig. 6).

## 4 Conclusion

In this work, a promising concept for an orthodontic functional appliance for the correction of class II malocclusions has been selected by the decision matrix for product development.

The concept consists of two-side guiding surfaces which forces the patient to bring the jaw into correct occlusion.

The interactive design of the device is accomplished by a software package in which designers and orthodontists can modify the design parameters and have an immediate visual feedback in a 3D virtual environment. The proposed approach allows obtaining patient-customized devices using a digital workflow. This approach should also permits orthodontist, designer and dental technician to interactively participate during device design and manufacturing phases in an innovative way, by a virtual workflow.

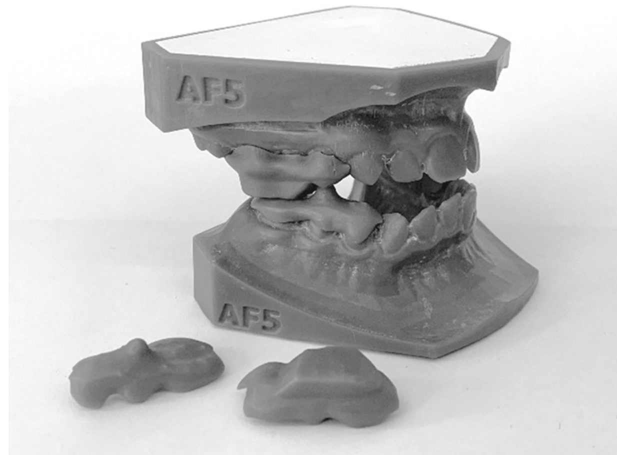



**Fig. 6** The additively manufactured prototype of the device

**Acknowledgements** This research was partially funded by the Grant “FSE 2105-51-11-2018” by Regione Veneto and the Grant “BIRD 190850” by Department of Civil, Environmental and Architectural Engineering, University of Padova.

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