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# PERSONALIZED PRODUCT DESIGN THROUGH DIGITAL FABRICATION

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## ABSTRACT

*Personalized designs bring added value to the products and the users. Meanwhile, they also pose challenges to the product design process as each product differs. In this paper, with the focus on personalized fit, we present an overview as well as details of the personalized design process based on design practice. The general workflow of personalized product design is introduced first. Then different steps in the workflow such as human data/parameters acquisition, computational design, design for digital fabrication, and product evaluation are presented. Tools and methods that are often used in different steps in the process are also outlined where in human data acquisition, 3D scanning, and digital human models are addressed. For computational design, the use of computational thinking tools such as abstraction, decomposition, pattern recognition and algorithms are discussed. In design for digital fabrication, additive manufacturing methods (e.g. FDM), and their requirements on the design are highlighted. For product evaluation, both functional evaluation and usability evaluation are considered and the evaluation results can be the starting point of the next design iteration. Finally, several case studies are presented for a better understanding of the workflow, the importance of different steps in the workflow and the deviations in the approach regarding different contexts. In conclusion, we intend to provide designers a holistic view of the design process in designing personalized products as well as help practitioners trigger innovations regarding each step of the process.*

*Keywords: Personalized product design, 3D scanning, human modelling. computational design, additive manufacturing, product evaluation;*

## 1. INTRODUCTION

Personalized products are products that are designed and manufactured to satisfy the needs of individual customers, ranging from functional requirements to aesthetics [1]. Enabled by Industry 4.0 and especially the advanced manufacturing techniques [2], the production goal of personalized products is shifting towards the added value for consumers, who are also engaged in specifying the requirements of, or even designing, their own products.

Personalized products can be grouped into three categories [3], i.e.,

- Personalization in Identity: This category focuses on the perception of the product; The unique form, texture, color, print, smell, taste, sound, feel, etc. provide added value for the customers; e.g. Apple® offers customer a service of printing his/her names on the AirPod®;
- Personalization in Capabilities: In this category, the design focuses on the personalized functions of the product. The unique performance of the products that is enabled by extra ingredients (electrical, mechanical, fluidic, and thermal

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[*] These authors contributed equally to this work.

components) demonstrates the added values of the product, e.g. adding electric roof in a car configuration;

- Personalization in Fit: It addresses the presence of the personalized product regarding the interactions between the product and the consumer, the environment and/ or other products that are used by the consumer. Physical characteristics of the product, such as shape, size, mass, area, quantity, color palette, etc. and the personalized interactions (e.g. comfort), present the added values of the personalized products in this category, e.g. custom fit shoes/chair/glasses.

Personalized products may help businesses in different ways, e.g. generate more sales; increase the profit margin; stand out from the competition; lower the inventory costs; have a deep insight of the needs of customers; increase customer loyalty and power the online business [4]. Meanwhile, personalized products also pose challenges for businesses as the products require flexibility and fast responses from the business [5]. In particular, a seamless information flow needs to be established across customer relation management (CRM), supply chain management (SCM), enterprise resource planning (ERP), the manufacturing process and the logistics [6]. It requires a complete transformation of business. Additionally, due to the nature of personalized products, they are hard to be reused. That is, an ill fitted/used product cannot be repaired or reused. Therefore, sustainability in the design of products, e.g. using more recyclable materials, design for recycling, should be addressed across the complete life cycle of the products.

In the area of design and manufacturing, traditionally, designers often design a series of products while taking into account the variations in consumers' wishes, sizes and other requirements. When designing personalized products, the designer is responsible for making a "modifiable" template. This template, often a script or computer program, processes user data (dimensions, text) and outputs the finalized design geometry and specifications [7]. Regarding manufacturing, agile manufacturing enabled by Industry 4.0 is able to quickly respond to the customer's demands [6]. As an important enabler of agile manufacturing, additive manufacturing methods (i.e. 3D printing) has been attracting attention due to its high flexibility and cost-effectiveness. Currently, additive manufacturing methods are widely used in manufacturing personalized products such as medical implants [8].

In this paper, with the focus on "personalized fit" products, we summarize the design process of personalized products and address the key steps based on design practice. The rest of the paper is organized as follows: first the general workflow of designing personalized products is discussed. Then the role of human data acquisition in the personalized fit is presented in Section 3. In Section 4, computational design is introduced as a bridge between designers and the data. Furthermore, design for digital fabrication is studied in Section 5, and methods of evaluations are explained in Section 6. Several cases studies are presented in Section 7 to highlight different steps in the design practice and finally, a short conclusion is drawn and possible improvements for the future works are highlighted as well.

## 2. THE WORKFLOW

Based on the design requirements and using the computational design approach, the general workflow (Fig.1) of designing personalized products can be divided into the following iterative steps: 1) Human data/parameters acquisition; 2) Generate design using computational design tools; 3) Design for digital fabrication; 4) Product evaluation. Besides, human models and 3D scanning techniques are often used for data acquisition, and to generate design templates for computational design.

*Human data/parameter acquisition*

In this step, data and parameters of individual body shapes are collected/generated. Besides parameters regarding the context of the design, two methods are often used in acquiring human body shape data:

- Direct data collection from 3D scanning, CT and/or MRI.
- Data augmentation from collected data, i.e., using a digital human model to generate (part of) the 3D human body shape.

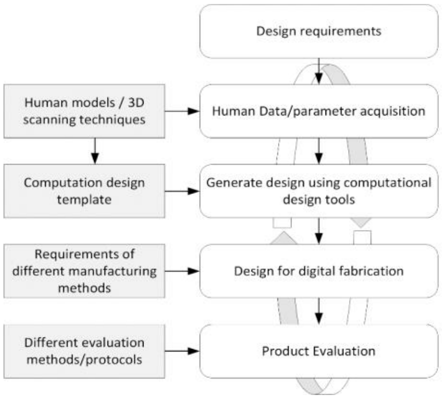


Figure 1: The workflow

*Generate design using computational design tools*

Prior to the personalized product design process, a set of design templates are often created. Instances of the template are controlled by the data (e.g. dummy human body shape), and/or parameters (e.g. the required length of a hand splint and the thickness of the splint). With the newly acquired data/parameters, a personalized design can be generated automatically based on those templates.

*Design for digital fabrication*

In this step, materials and manufacturing requirements are used as the inputs, and the personalized design is further tuned for the selected manufacturing methods, selected materials and optimized for the specific manufacturing process.

*Product evaluation*

A product needs to be evaluated regarding its functionality and usability. For personalized products, extensive evaluations should be conducted on different boundary conditions (with a safety margin) regarding engineering, manufacturing and ergonomics factors. Evaluation results shall be feedback to the designer for the next iteration of the design.

In personalized product design for digital fabrication, a series of software tools can be used. For human data acquisition based on 3D scanning methods, tools such as Geomagic®, Agisoft Metashape® are often used. In the category of computational design, Rhino® (and Grasshopper®) is frequently mentioned. For computer aided design (CAD), Solidworks®, CATIA®, NX®, Autodesk Fusion® etc. are often used and in the area of computer aided engineering (CAE) analysis, Ansys®, Abaqus®, CATIA®, NX®, Adams®, SimScale®, etc. are tools that are often applied. For computer aided-manufacturing (CAM) tools, besides machine specific tools, 3D expert®, Cura®, Slic3r®, Materialise 3-matic®, etc. are frequently applied in simulation and toolpath generation. It is worth mentioning that the uses of those tools are not exclusive but complementary. Designers often select tools based on the desired functionality, usability, familiarity, and availability.

The aforementioned workflow and the detail steps are more indications rather than guidelines. In practice, designers often take short iterations to improve the design, or sometime they even swap the steps following the needs of a particular context. For instance, in the process of design for digital fabrication, designers may modify the computational design templates to fit the manufacturing requirements; or they will simply print a (part of the) prototype to verify the set parameters. Another example is that for the known scenarios, CAE simulations are always performed prior to the manufacturing process to tune the design. However, CAE simulations are also conducted in the evaluation for a comparison of the experiment and the simulation results to find protentional problems in setting up the simulation, e.g. boundary conditions, material properties. The new scenario discovered during evaluation are often simulated as well for the next design iteration.

## 3. HUAMN DATA/PARAMETER ACQUISITION

The shape of humans differs by nature. "Personalized Fit" requires not only the desired parameters of the product, but also data regarding the 3D body shape of the individual. For acquiring human 3D shapes, two methods are often used: 1) 3D scanning - to acquire the exact body shape of individuals; and 2) Data augmentation using digital human models.

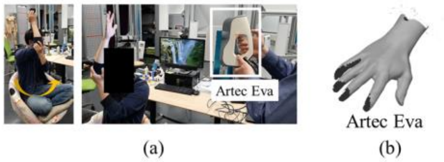


Figure 2: 3D scanning of human hands using Artec® Eva® scanner, courtesy of [9]

### *3D Scanning of human body*

Many techniques, e.g., structured lights, time-of-flight scanning, laser scanning, computed tomography and photogrammetry, have been developed and used in digitizing the 3D shape of the human body. In real life scenarios, the challenges in digitizing human-body parts are mainly the complex geometry and the potential movement of the human body during the scanning process. Figure 2(a) presents the scanning of the hand where an Artec Eva® was held by a researcher. A participant sat on a rotary chair and raised his hand over his head. While the subject was asked to keep the body and the hand as stable as possible, a second researcher (not shown in the picture) slowly rotated the chair with instructions from the first researcher holding the scanner. After a few tries, it was possible to acquire the scan of the hand within 40-50 seconds. However, the quality of the scan (Fig.2(b)) strongly depends on the cooperation of the subject and researchers [9]. To solve this problem, researchers/practitioners sometime use another strategy which is to scan the negative shape, e.g. podiatrists use the scan of the foot imprint on the foot impression foam to design customized orthotics [10]. However, this process can only get the shape information of one posture.

In the area of high-speed digitization of human body shapes, 3D optical scanning and photogrammetry are two techniques that are often used. 3D optical scanning methods project either a laser or a structured light pattern onto a region of interest (ROI). The images of the ROI are then captured by cameras. Based on image processing and the use of the triangulation method, the external shape of the ROI can be acquired. Examples of those scanners are the Artec Eva®[11] and Capture 3D® [12] .

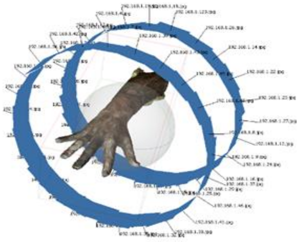


Figure 3: 3D hand reconstruction using photogrammetry (blue planes are identified camera image planes), courtesy of [9]

Photogrammetry is the process of creating a 3D scan of a human/object using multiple images of the object taken at different angles. The principle of photogrammetry is to match the same featured points (e.g. pixels or regions) in overlapped regions of different images and then compute the coordinates of those points using the triangulation method. The Scale-Invariant Feature Transform (SIFT) [13] is a typical algorithm used to identify those featured points. Examples of software tools that use photogrammetry technique to construct 3D models are Agisoft Metashape®[14], and Meshroom®[15], a free and open-source 3D reconstruction software. Figure 3 shows the process of reconstructing a human hand 3D model from 50 images using Agisoft Photoscan®.

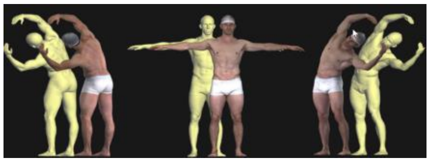


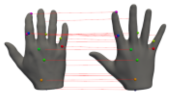
Figure 4: 3dMD® scanning system (courtesy of [16])

Many commercial scanners often combine photogrammetry with another technique. A typical example is the 3dMD® scanning system [16], which is built on multiple Modular Camera Units (MCUs). MCUs utilize a hybrid of stereo photogrammetry and structured light technology. Depending on the needs of the applications, the system can be configured to capture the shape of the whole body as well as different parts.

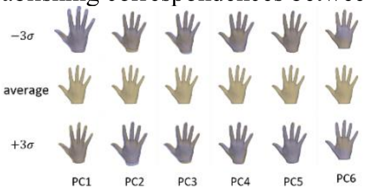
### *Digital human model*

A digital human model is a parametric virtual representation of the variation of a human characteristic based on large sample database. Based on a few anthropometric measurements, it is possible to use a 3D digital human model to approximate shapes of the human body with reasonable accuracy.

(a) 3D scans of the hand



(b) Establishing correspondences between scans



(c) Change the coefficient of the principal components (PCs) of the hand SSM model

Figure 5: Building a hand SSM model

A digital human shape model can be constructed based on different requirements using different tools. A statistical shape model (SSM) of the human body, which can represent the 3D shape with a limited number of parameters with a certain accuracy, can be utilized as a high-fidelity digital representation of the body in many applications. In general, a SSM can be created based on digitization, establishing correspondence and modelling these three steps.

- Digitization: In the digitization step, many 3D scans representing the whole population are collected. For example, Fig.5(a), we show some scans of the human hands. All scans are triangle meshes, i.e., the surface is represented by triangles that are connected by their shared edges or vertices.
- Establishing correspondence: In this step, the correspondences between vertices/triangles of a triangular mesh and a reference model (template) are established as Fig.5(b). Many algorithms were developed for this purpose, for instance, the non-rigid iterative closest points methods (non-rigid ICP, e.g. [17]).
- Modelling: In this step, all meshes are aligned together (brought together as close as possible). Possible posture variations can be corrected using different methods, such as using embedded skeletons [18]. A statistical shape model can be built based on the mean of corresponding vertices and the variances of each vertex regarding the corresponding vertex in the mean model. The variances (Fig.5(c)) can be simplified using dimension reduction methods, e.g. the principle component analysis method, which is a dimension-reduction tool that can be used to reduce a large set of variables to a small set that still contains most of the information present in the large set.

An example of online digital human models is the DINED database [19], developed in TU Delft as Fig.6. Since 2000, the focus has been moving to the application of 3D scanning in anthropometry. This has resulted in various 3D data collection as well as research into the analysis and presentation of 3D anthropometric data and its applications in design. Designers can easily acquire a human shape model based on a few parameters, e.g. the statue, BMI. It is worth mentioning that the accuracy of the model strongly depends on that if the target user is in the population that the datasets were that the model built on, the inputs of the users as the default parameters of the model is often the mean values of the population.

|  | Measure | Persona 1 | Group 1 |
|---|---|---|---|
| X | Stature 2 | 1800 mm | 1500 – 1840 mm |
| Y | Face length 85 | 129 mm | 98 – 114 mm |

N 846 R 1 μ(X) 1754 σ(X) 106 μ(Y) 117 σ(Y) 9

Figure 6: The Mannequin tool from the DINED platform [20]

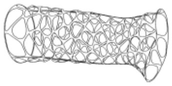
## 4. COMPUTATIONAL DESIGN

Computational design has the possibility to help designers explore the solution space in a systematic and comprehensive manner by utilizing the computing power of computers and the intelligence of embedded algorithms. Using computational design, the role of designers is evolving from designing an explicit shape, to programming instructions for a computer to generate up with (unique instances of) a design, automating steps of the design process.

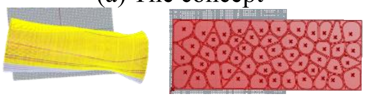
The basis of the computational design is computational thinking [21]. Computational thinking is a systematic approach to tackle ambiguities of design, sophistications and open-ended optimal problems through exploiting fundamental computer science principles and practices. Thus, computational thinking contains a large variety of computational-related components, while we list the most design-oriented components as follows:

- Abstraction: which encourages designers to focus on the core idea of the design instead of being lost in the complexity and details;
- Decomposition: which allows designers to logically divide a new challenge in the field into several related problems and increase the manageability of the workflow, e.g., using the divide-and-conquer strategy;
- Pattern recognition: which help designers find the “rhythms” in the design to simplify and accelerate the design process;
- Algorithm: which translates the designers’ idea to a set of ordered instructions that utilize the computing power to automate the design process and optimize the design.

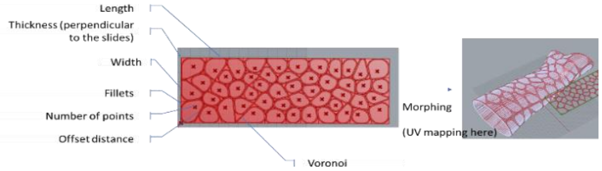
Figure 7 shows an example of using computational thinking in design. The task in this case is to design a personalized splint for a patient with bone fractures on the forearm as Fig.7(a).



(a) The concept



(b) Abstraction and decomposition



(c) Pattern recognition & Algorithms

Figure 7: An example of using computational thinking in design

In the abstraction of the design, we notice the similarity of human forearms shapes, and it is possible to design a "reference design" of the splint as a template on a dummy shape of the forearm. Further thinking indicates that the splint can be built on the forearm by mapping a planar pattern as Fig.7(b). In the construction of the model, the holes on the planar shape can be automatically generated by different algorithms, e.g. the Voronoi algorithm. And the planar shape can be morphed to the forearm using UV mapping (Fig.7(c)).

For a geometric model generated by computational design tools, it often utilizes a set of parameters. Parametric design/modelling is the "*creation of a 3D geometric model using a series of pre-programmed rules or algorithms based on data and design parameters*" [22]. Using parametric design, the 3D model can be generated and updated automatically based on the data and parameters specified by the designer(s). Design parameters of personalized products can be intrinsic and extrinsic parameters of 3D shapes:

- Intrinsic parameters of a 3D shape can be interpreted as a human description and interpretation of a shape or object [23]. In the case of the Voronoi Bicycle Helmet (Figure 8), an intrinsic parameter of the helmet can be the width of the helmet;
- Extrinsic parameters can be considered as parameters of geometrical entities which actually define the shape or object. Computers use extrinsic parameters to generate and update a 3D model, e.g. the position of each vertex in the helmet.

With the human centered design principle, it is important that the parameters of a parametric design should be interpretable for personalized products, preferably by the customers to drive a design towards their needs and wishes.

Figure 8: The Voronoi Bicycle Helmet designed by Yuefeng Zhou, Zhecheng Xu and Haiwei Wang

*Generative design & Topology optimization*

The idea of generative design is to explore the design space in a systematic and automatic manner, and thus to generate the optimal design under prescribed design specifications. It is an algorithm-driven design process. Example approaches include shape and topology optimization, shape grammar-based design, machine learning based design methods, among others [24]. For instance, Wu et. al. utilized Generative Adversarial Network (3D-GAN) to generate 3D objects from a probabilistic space by leveraging recent advances in volumetric convolutional networks and generative adversarial nets [25].

One widely recognized generative design technique is topology optimization [26], which has been increasingly used in personalized product design, either for reducing the weight without compromised to the stiffness of the design, and/or for a better design aesthetic. In topology optimization, the problem of structure design is reformulated as finding the optimal distribution of material in a discretized design domain. The optimized layout is not restricted to its initial topology, opening up possibilities for superior structural performance over manual designs based on engineers' intuition and experience. Topology optimization aims to find the optimal structural layout for certain applications such as finding a structure that is optimized for maximum stiffness under a given load or torque. The optimization problem is often solved using an iterative approach. Figure 9 presents panels of aircraft interiors for which an innovative topology optimization method [27] was applied in the design process.

Figure 9: Panels of aircraft interiors of the flying-v project [28]

## 5. DESIGN FOR ADDITIVE MANUFACTURING

Additive Manufacturing (AM), or 3D Printing is a Digital Manufacturing technology that is increasingly being used in the architecture, engineering, and construction sector, and could also be considered a prerequisite for fabricating many personalized fit designs [29].

Depending on the requirements of the design, an AM process and material needs to be selected from the large variety of available AM processes and materials. Fused Deposition Modelling (FDM), Stereolithography (SLA) and/or Selective Laser Sintering (SLS) are often used in printing plastic products, and for metal parts/products, Powder Bed Fusion, Direct Energy Deposition and Binder Jetting are often applied. Recent developments on printing soft materials, conductive materials [31] [32] and multi-material printing [33] offer new opportunities for personalized products. For instance, the Stratasys J735 multi-color/material 3D printer uses the polyjet technique and is able to print with multiple materials, ranging from rigid opaque materials, to transparent and rubber-like soft materials. Figure 10 presents a personalized dress that was printed using a multiple materials [34].

For optimal performance of the printed product, it is essential to consider different parameters of the chosen AM process. AM-related design considerations need to be taken into account from the beginning of the design process. Each AM system has a set of design rules. For example, design rules for wall thickness, tolerances, and possible overhangs directly influence the possible structures that can be fabricated. Also, the engineering properties, e.g. thermal or mechanical properties, of 3D printed materials differ from the original materials, mainly due to the non-uniformness introduced by the manufacturing process.

Next to design rules, there are also manufacturing-related decisions that need to be taken and which have an influence on part properties. A well-known example in the use of Fused Deposit Modelling (FDM) is the building orientation as shown in Fig.11. Different building orientations will result in different support structures, different stiffness of the prototype/products, different surface finishing. Details of those constrains are available in different knowledge bases, e.g. [35]. Referring to the 3D printing practices, e.g. FDM, many practical issues need to be considered in setting the printing parameters for a specific printing technique, or even for a particular machine, such as build plate adhesion type and strategies to avoid warping.

As many personalized products come in contact with the user, it is important to choose materials that can be in contact with the human body without any adverse effects, i.e. biocompatibility is recommended for such products. The FDA (U.S. Food & Drug Administration) approved many Class I and Class II materials that can be used to construct personalized products, such as Polylactic acid (PLA) filaments or PETG Filament, which can be used in Class II products [30]. Regarding metals, Titanium Alloy (Ti-6Al-4V) is often used in medical implants.

Figure 10: A 3D printed dress, design by Iris van Herpen, presented at *Galerie de Minéralogie et de Géologie* in Paris, Photographed by Yannis Vlamos and courtesy of [34]

## 6. DESIGN EVALUATION

Personalized products can share the same design template, but the model has to be adjusted based on different body shapes. For example, the thickness of the hand splint might need to be increased for larger hands as Fig.12. Due to size variations, it can be difficult to set one evaluation standard. An evaluation strategy needs to be set regarding different boundary conditions of the design based on the functionality and usability of a product.

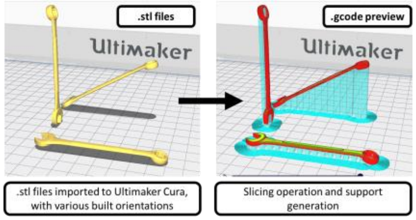


Figure 11: An example of adjusting printing parameters according to needs, i.e. preview of a part with different building directions using FDM

Figure 12: A design of hand splints, but sizes may vary according to different hand shapes [18]

*Scenario creation*

Usage scenarios with the user(s), the product(s), the environment and possible interactions may help the designer to have a better understanding of the boundary conditions for evaluating the products. A possible procedure in defining the scenarios can be:

1. Define the persona: It is worth mentioning that personalized products differ due to their nature. Multiple personas are often needed regarding personalized fit, e.g., P5 and P95 of the population, or randomly generated examples for verification;
2. Define the starting point and the tasks of the scenario(s); Multiple scenarios are often needed in the evaluation as well;
3. Explore the stakeholders and the product use environments;
4. Write different stories regarding the user activities in different scenarios;
5. Explore the extrema (boundary conditions) regarding the use of the product in those stories. For the functionalities of the product, the boundary conditions can be identified through different usage scenarios and manufacturing variations. Mechanical, electrical, fluidic, thermal properties are often evaluated against those boundary conditions.

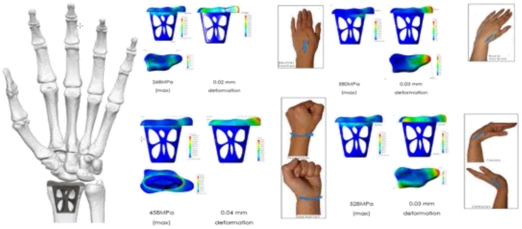


Figure 13: FEM simulation of a new patient-specific prosthesis for resurfacing of the distal radius based on different scenarios (CAE tool: Solidworks® ), Courtesy of [36]

*Functional evaluation*

As indicated in Section 2, CAE simulations can be use prior to the manufacturing and/or in the evaluation of the product, depending on the requirements and the case. Through CAE simulations, it is possible to predict/analyze the performances of a prototype in a cost-effective manner. Figure 13 presents the Finite Element Method (FEM) simulation of a patient specific implant in different scenarios (with different loading conditions).

*Usability evaluation*

Subjective evaluation is often used in the usability evaluation. Questionnaires are an important tool(s) in subjective evaluation. There are many types of questionnaires for evaluating different types subjective feelings, and using verified questionnaires may accelerate the evaluation process. Figure 14 presents a simple comfort/discomfort questionnaire, which is often used to evaluate the level of comfort/discomfort that the user feels before, during and after using the product. "..." in the figure can be changed by different contexts. A list of questionnaires for comfort evaluation of different products can be found in [37].

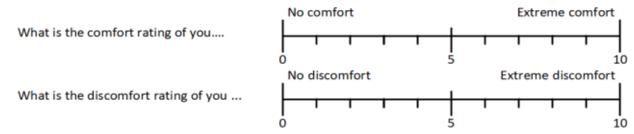


Figure 14: Comfort and discomfort questionnaire

Objective measures regarding the user and the environment are also often used in the evaluation [38]. Parameters of the environment include vibration, light, noise, smell, etc. Physical parameters of the user(s) include anthropometry, contact interface pressure, movements, etc. Physiological parameters of the user(s) include heart rate, heart rate variability (HRV), blood pressure, etc. Literature indicates that there are many relations between/among objective measures and subjective feelings, e.g., features in HRV are associated with the stress level [39]. With the digital twin technology [40], and especially the embedded real-time sensors in the products, the future personalized product might be able to predict the feeling of the user or even change its form for a better performance.

*Experiments design*

Experiments or trials are the “gold” standard in product evaluation. In the design of the experiment to evaluate the design, the following aspects might be considered:

- The hypothesis(s) to be testified by the experiment;
- The setup and the location of the experiment;
- The metrics (function & usability) will be used in the evaluation;
- The measurement methods and devices that may generate data to support the metrics;
- The data management plan (DMP) and the post-processing methods of the collected data;
- The target users of the products, i.e. experiment participants should be representative for the target population;
- The safety of users in the use of the product; a risk management matrix can be a good addition;
- In any experiments where the user(s) is involved, we need to consider the ethics and apply permissions from the ethical committee (incl. informed consent);

*Risk management*

Risk management is an important requirement in the development of personalized products especially many personalized products, such as a hand splint for managing fractured bones, can be categorized as Class I or II medical devices [41]. For Medical devices - Application of risk management to medical devices (ISO 14971:2019 [42]) specifies the terminology, principles and a process for risk management of medical devices. Following the scenarios defined before, according to the functional and usability evaluation results, the designer can often use a risk assessment matrix [43] to explore the ways of mitigating the potential risks, especially regarding the severe and catastrophic risks.

## 7. CASE STUDIES

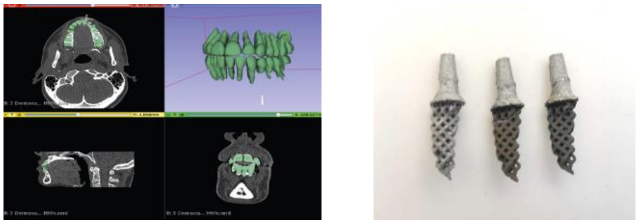
In the past decade, “personalized product design though digital fabrication” is a focus of the Faculty of Industrial Design Engineering (IDE) at Delft University of Technology (TU Delft), from both research and education perspectives. For instance, in Fig.15, students’ design of personalized products fabricated by 3D printing are presented. The authors have explored and developed the workflow, advanced algorithms. Meanwhile, they also explored various novel applications in the area of personalized designs. In this paper, based on those design practices, we summarized our experiences and present the outcomes as the “best practice” for personalized product design though digital fabrication. In the rest of this section, we present some case studies as typical examples. It is worth mentioning that in different cases studies, the focuses on different steps of the workflow might be different, depending on the context of the design.

Figure 15: Personalized products fabricated by 3D printing

*Case: Personalized Dental Implant – Courtesy of* [44]

This project uses the computational design method, to design the lattice structure for a personalized dental implant. Currently, the process of placing dental implants is a long process with a 3-5 % failure rate, mainly caused by the lack of osseointegration (the integration of living bone and an artificial implant) and infection. This patient-specific implant has a porous structure to promote osseointegration. Another advantage of using this product is that bone healing after extraction (of the tooth) is not required, which saves 3-6 months of the procedure.

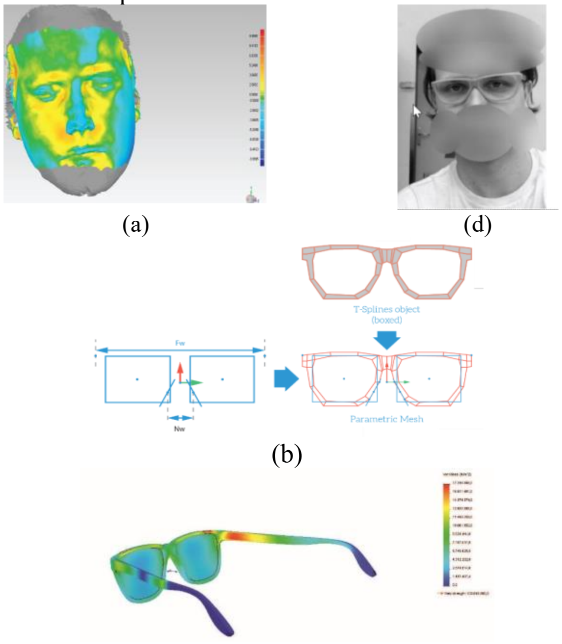
In the personalized design, the shape of the root of the tooth was acquired by a cone-beam computed tomography system (CBCT). Using image segmentation software, the shape of the root can be retrieved (Figure 16(a)). A lattice structure was designed following the shape of the root using Rhino® and Grasshopper®. Such porous structure was created to promote



(a) (b)

Figure 16: Design of patient specific tooth implants, courtesy of [44]

osseointegration, where bone can grow into the pores of the structure for a better fixation. The prototypes were made of Ti6Al4V alloy manufactured by selective laser melting (SLM). The surface of the implant was treated by plasma-electrolytic oxidation (PEO) with silver nanoparticles to create an antimicrobial surface. Figure 16 (b) shows the printed implant (left), surface treated by PEO (middle), surface treated by PEO and silver plating (right). The design was validated with oral surgeons and all of them see added values in the patient-specific design as compared to current solutions, which only have a set of "standard shapes".



(a) (d)

(b)

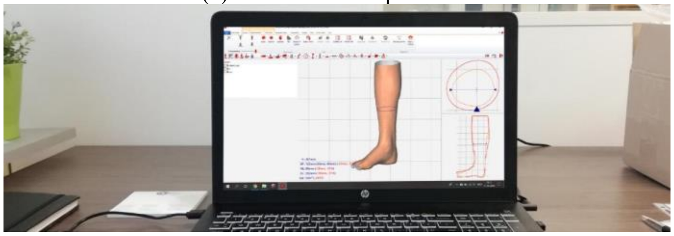
(c)

Figure 17: Personalized sunglasses, courtesy of [45]

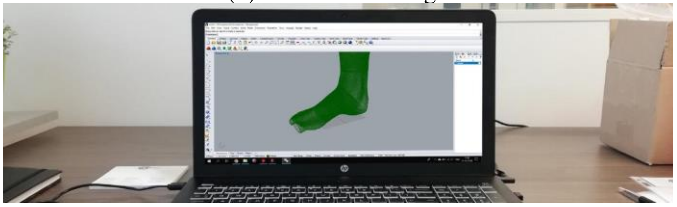
### *Case: Personalized sunglasses*

It is difficult for the customers to find sunglasses that they like and fit to their face. Personalized sunglasses with adjustable aesthetic style as well as ergonomics fit might meet the needs of consumers. The aim of this project is to develop customized sunglasses that fit individual users. Photogrammetry technique was selected for acquiring human face models. The user was asked to make a video of their face while turning his/her head from right to left in 30 seconds. A 3D model can be constructed based on photos extracted from the video with an accuracy of 1 mm regarding the critical areas of the face for wearing glasses, such as nose bridge, ears, and eye positioning. (Fig.17(a)). Several templates of sunglasses were designed in different styles. For each template, parameters were introduced to adjust the template for the best fit regarding a given 3D scan. An example is presented in Fig.17(b) where parameter Fw is the width of the face and Nw (a crucial parameter for the user's comfort) is the width of the nose bridge. The Selective laser sintering (SLS) printing method was selected as the manufacturing method where PA12 was selected as the material. FEM simulations were conducted on the small and the large designs in different scenarios to verify the stiffness of the personalized sunglasses structure (Fig.17(c)). Several prototypes were also produced and tested by the users and Fig.17(d) shows one of the prototypes worn by the user.

(a) Human data acquisition



(b) Human modelling



(c) Computational Design

(d) Functional evalution (e) User evaluation

Figure 18: Design a patient specific AFO, courtesy of [46], in (e) the blue/grey block is the pressure gauage)

### *Case study: Ankle Foot Orthosis*

Patients diagnosed with drop foot syndrome often encounter difficulties in walking. An Ankle Foot Orthosis (AFO) is an orthopedic aid that limits the plantar flexion of the foot to ensure a safe walking gait for the patient. Currently, these AFOs are often acuum formed over a machined foam following the shape of the patient's leg. In this case study, we present the design of the personalized AFO using the 3D scanning and the additive manufacturing method.

The 3D shape of the lower leg of the patient was scanned first where some extra measurements were collected manually (Fig.18(a)), mainly to make up the missing part(s) in the 3D scans. The 3D scanning data was post processed (Fig.18(b)) and then the AFO was designed using computational design tools, in this case Rhino® and Grasshopper® (Fig.18(c)). The AFO was printed and tested regarding engineering parameters (Fig.18(d)) as well as usability (Fig.18(e)).

## 8. CONCLUSION

Personalized product design brings added value to the product(s), meanwhile it also poses challenges to the design process. In this paper, we give an overview of different steps of the personalized product design process based on the best practice. Within the proposed iterative workflow, the body shape of the user(s) is collected first, either by 3D scanning or based on digital human models. Computational design tools are used to fit an existing design template to the acquired body shape. With design for digital fabrication tools, the design is further optimized for a better manufacturability. Both functional and user evaluation methods are introduced for evaluating the design. We want to address that this paper is based on the design practice, and we expect that it will give designers a holistic view of the design process in designing personalized products as well as help practitioners trigger innovations regarding different steps in the process.

Meanwhile, our design practice also indicated that there are many aspects can be improved in the workflow. In the area of human data acquisition, shapes of human body (parts) used in the design is in mainly 3D, which often resemble a static pose. Research on acquiring 4D shapes and using those dynamic body postures in design is undergoing. For computational design, more advanced algorithms in the area of generative design and topology optimization are under development. In design for digital manufacturing, different types of digital materials will be introduced and new additive manufacturing methods, e.g. cold spray, are under investigation. For product evaluation, engineering properties of materials manufacturing by additive manufacturing methods, especially about their anisotropic properties, are being embedded in the material database for a better prediction of the behaviors of the product in use. Among all potential improvements, perhaps the most important is to develop a software platform to support personalized product design through digital fabrication. Currently, many software tools are used in the design process, and designers have to shift among different tools for the desired functions. This is expensive regarding both the cost and the needed skills. A platform which is able to synthesize the needed functions may help designers avoid possible errors in swapping tools and accelerate the design process, therefore improve the effectiveness and the efficiency in designing.

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