Application of Robust Design Techniques for 3D Printing on Textiles

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Abstract. The goal of this article is to show the opportunities and limitations of Robust Design techniques in the design process of developing new applications that combine 3D printing and textiles. Two case studies are discussed in which various elements of Robust Design techniques were used to understand and improve the adhesion strength of 3D printed material on fabric and the pressure exerted by a pneumatic actuator for the purpose of acupressure point manipulation. The advantage of combining 3D printing and textiles is the possibility to transform the properties of a regular textile material by using additive manufacturing. This can be beneficial for the design of specific products and contexts, for example to add mechanical or electronic functions. The experiments presented in this paper were executed as part of an undergraduate course taught to design students in the context of an Industrial Design program.

Keywords: 3D printing · Textile · Robust design · Pneumatics · Design method

1 Introduction

The combination of 3D printing and textiles creates opportunities for design in which rigid objects can be enhanced with embedded flexibility, and functionalities can be integrated into the soft material [1, 2]. The advantage of such a process is the possibility for transformation of a regular textile material into a more functional product using additive manufacturing [3, 4]. Other studies have sought to improve the adhesion of 3D printed materials onto textiles, for example by combining 3D printed polymers with different textile materials and fabrics [5]. However, the fact that textiles comprise a wide variety of different materials with different constructions and cloth architecture, as well as the complexity of interface phenomena with polymers make it a challenge [6]. In particular, the combinations of all these factors can be interdependent, in which small changes (such as environmental conditions, product deterioration, manufacturing variation) can have a large impact on the desired results.

The objective of Robust Design Methodology (RDM) is to generate or identify design solutions that are robust, that is, insensitive to sources of unwanted variation or noise factors [7]. By reducing–during the design process–the instability brought about

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by the uncertain future, environmental variation, robust design improves both the quality of the functions and the satisfaction of the users [8].

The goal of this article is to explore how RDM can be used to enhance the design process of 3D printing on textiles. The process that will be discussed consists of the following four steps, first select the factors, as noise and control factors, using a simple screening test. Second, create an array in order to begin the systematic testing that characterizes robust design process. Third, design and execute experiments that can validate the selected factors and determine the magnitude of their effects on the response. Fourth, and finally, analyze the results of the experiments using a two-step procedure to identify the "optimal" factor settings that minimize the variance and adjust the mean to target.

2 Background

Two case studies are introduced, both of them projects undertaken as part of an Industrial Design course focused on Robust Design. Case Study A was a preliminary process focusing on finding out the best adhesion properties between textiles and 3D printing. Case Study B was conducted one year after Case Study A and used the insights of previous case study to design a real-world application.

2.1 Robust Design

A robust product or a robust process is one whose response is least sensitive to all noise factors. The principle of Robust Design Methodology is that the product's response depends on the values of the control and noise factors through a nonlinear relationship. This nonlinearity can be exploited to achieve robustness [8]. Figure 1 shows a visual overview of parameters considered in the Robust Design model. The parameters (also called factors) that influence the quality characteristic (that measures the product function) can be grouped into three classes: Signal Factor, Noise Factors and Control Factors.

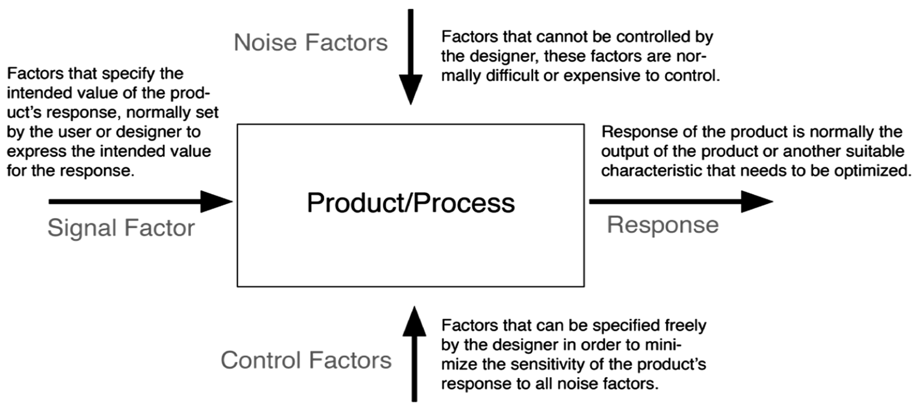

Fig. 1. Visual overview of the Robust Design Methodology adapted from model by Phadke [8].

2.2 Case Study A: Adhesion Strength of Textiles and 3D Printing

The aim of the first case study was to use robust design techniques in the process of understanding factors affecting the adhesion strength between a textile polyester substrate, similar to many used for modern clothing, and printed on top of it a specific shape using 3D printing technology. The goal was to achieve adhesion in the design, which allowed for a robust printing quality that would be repeatable in different situations. The results of applying this method could enable users to print their own design on their clothes, providing them with special functions, such as features for protection, safety or decorative elements (a concept sketch is shown in Fig. 2a).

For the fabric, a polyester textile was chosen because it is a fiber commonly used in the textile industry to manufacture clothing. Robust design methodology was used to select and determine the main factors such as, printing shape, printing material, and others. The goal was to determine which of the factors contributed more to adhesion in the design, allowing a printing quality that can be repeated over time and across multiple different situations, which will allow the user to achieve a similar result each printing.

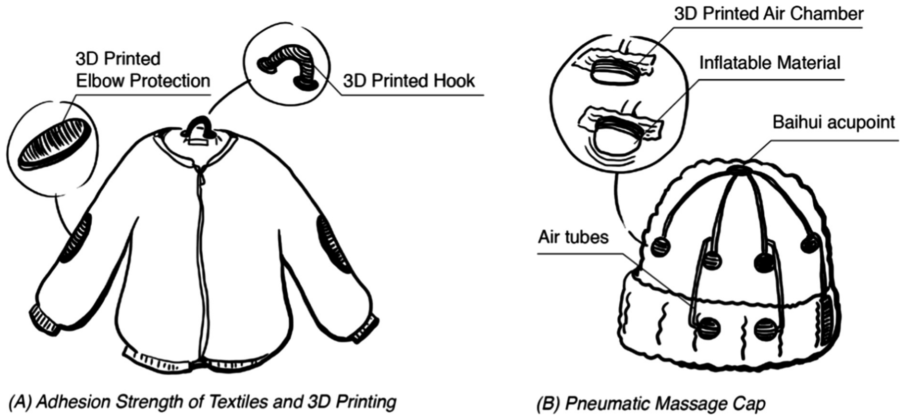

Fig. 2. Visual overview of the concepts that were developed in the two case studies.

2.3 Case Study A: Adhesion Strength of Textiles and 3D Printing

In the second case study a pneumatic massaging cap that could stimulate certain acupressure points on the user's head was developed (a conceptual sketch is shown in Fig. 2b). The goal of this cap was to reduce the risk of patients with a high probability of suffering a stroke by accurately achieving the required pressure. Potential stroke patients include heart disease patients, smokers, elderly hyperlipidemia patients and so on [9]. These stroke-prone groups could benefit from preventive measures to avoid the occurrence of stroke.

3D printing was used to print the encapsulation of the air chambers directly onto the fabric of the cap, to avoid the influence of glue and other bonding media on the pressure intensity, comfort, connection stability and durability. Moreover, because the strength of the pressure needed to be precisely controlled, 3D printing was used to customize the parameters of the air chambers in the massage cap.

The principle of the concept is based on Traditional Chinese Tuina manipulation, which is an important part of traditional Chinese medicine, with a unique and potentially curative effect on treating diseases and health care [10]. Acupressure points (also called acupoints) describe the many nerve endings and blood vessels [11], for example, the Baihui acupoint on the top of the head (shown in Fig. 2b). In this case study the students aimed to simulate manual acupoint pressure massage by exerting accurate force on specific acupressure points on the head using an automatic actuator. Pneumatic actuators were chosen as a technique to exert the pressure instead of other actuation techniques (such as vibration). Pneumatics allow for a greater force which is required for the intended point pressing manipulation, and moreover, the effect is easier to control than other actuation techniques.

3 Approach

A crucial step of the Robust Design Methodology is to select the Target Response, Signal Factor, Control Factors and Noise Factors. The selection of these parameters is based on the intention of the designer for the product, and normally entails a delicate balance between engineering constraints and user requirements. This section will discuss the considerations for selecting the parameters for both case studies. Since the case studies were conducted sequentially and have some overlap with each other based on the general topic of 3D printing on textiles, some of the conclusions of Case Study A helped to inform the decisions in Case Study B.

3.1 Parameters Case Study A

The goal of this project was to 3D print elements on fabric. Crucial for this application was that the required force to pull off the 3D printed elements should be as large as possible. Current problems with 3D printing and textiles can be attributed to the limited adhesion with the fabric, which will affect the durability of the use; therefore, the

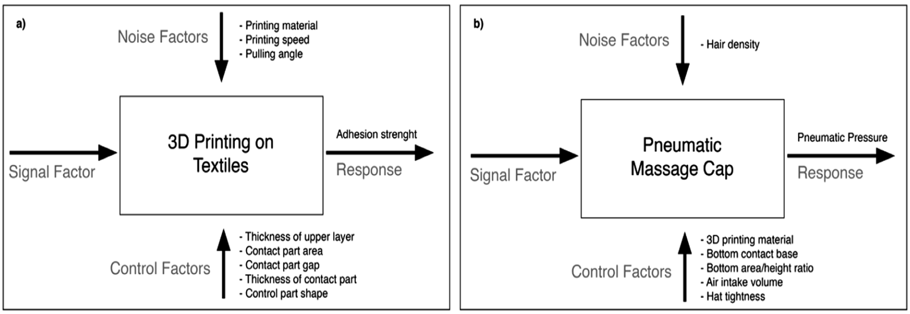

Fig. 3. Models of the parameters selected for Case Study A and Case Study B.

adhesion strength was identified as the main *response*. Since this Robust Design model is defined as a static system, it was not required to choose a *signal factor*.

The students proposed several factors associated with the adhesion strength and divided them into *control factors* and *noise factors* shown in Fig. 3a. The *control factors* are related to the structure of the printed component, especially the parameters to adjust the contact and space between the printing material and the textile (several control factors are illustrated in Fig. 4a). For example, a larger contact part area would be expected to achieve a stronger adhesion, but if the contact part gaps are too small problems with the print might occur. Therefore, a balance between the contact and gap would be the ideal situation.

The *noise factors* are settings that relate to the 3D printing process, since this process is supposed to be conducted by the user under different situations it is harder to control. For example, different printing materials and different printing speed could be used. Another factor which would vary in real-life applications, is the force that pulls the 3D printed part off the fabric (the angle and speed at which it's pulled). Therefore, the pulling angle is also considered a noise factor.

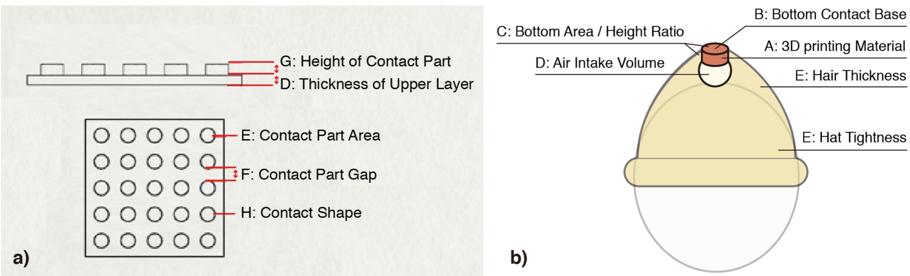

Fig. 4. Illustration of the control factors that were selected for Case Study A and Case Study B.

3.2 Parameters Case Study B

The *target response* in this project was chosen as the required force to be exerted on the head using the pneumatic actuator in the cap. The exact value was based on a study which measured and compared the pressure that was exerted by several massage methods [12]. Thumb-pressing is a common manipulation method for acupoints, which normally requires a force in a range between 6 N and 244 N. The minimal value of the range (6 N) is a suitable force for the more fragile parts of the body, which would be appropriate for the head. Since the students modelled this application as a static system, no *signal factor* was selected. However, we intended to use the *air intake volume* as a control factor which could be scaled to the target response of 6 N, since this is the value which eventually should be controlled by the user (a larger air intake will result in more pressure). For this user controllable value, the students proposed a range between 20 mL and 40 mL.

The *control factors* for this case study are shown in Fig. 3b and further illustrated in Fig. 4b. The 3D printed air chamber that contains the inflatable material plays a practical role, because it restrains the volume of the gas, to produce a certain pressure on the scalp. The *ratio of bottom area over the height* of the 3D printed air pressure chamber was included because the area under a certain volume was taken into account when transferring pressure into force. Besides PLA filament, a flexible TPU material was also used for 3D printing the air chamber on top of the fabric. Because the flexible 3D printing material will deform due to the influence of the pressure, which has an impact on the volume, the *printing material* is also selected as a control factor. When wearing the cap, the elasticity of the cap could affect the effectiveness of the pressure. For example, when the elasticity is loose, the inflatable material would move further away from the acupressure point, and therefore result in exerting less pressure on the head. Therefore, the *tightness of the cap* was selected as another control factor. The final control factor was whether the 3D printed air chamber *included a bottom*. When the inflatable material in the air chamber is inflated, the gas exerts the same pressure on all directions of the air chamber. Therefore, when the material printed on the bottom constrains the movement of the inflatable material, it can only bulge in the direction of the scalp, and therefore, increase the pressure. When the 3D printed air chamber has no bottom, the inflatable material will stretch the elastic fabric and reduce the pressure on the scalp. As *noise factors* in this project the students selected the density of the wearer's hair, since this parameter is impossible to control by the designer but could have an influence on the effectiveness of the pressure massage.

4 Experiment Design

A critical step of Robust Design is to determine the effects of several parameters, in order to come to levels for a set of parameters for which the response is least sensitive to the noise factors. A technique to evaluate this is to conduct a matrix experiment, in which the setting of the various parameters are changed from one experiment to another. *Orthogonal arrays* have been used extensively in planning industrial experiments, since they can help to reduce the number of experimental runs to a reasonable number, in terms of cost and time [13]. In order to create an experiment, it is required to define the number of factors to be studied, the number of levels for each factor, identify any 2-factor interactions to be studied, and to take care of the difficulties in running the experiment.

4.1 Experiment Case Study A

As previously discussed, the students identified five control factors and three noise factors in relation to the adhesion quality of 3D printing on fabric. Based on a screening experiment, preliminary data of the factors identified were collected. For instance, the height of contact part area should be less than 2 mm. All eight factors (control and noise) with their levels are shown in Table 1. The students choose the L18 array, which has 18 experiments with eight control factors including, one two-level control factor, and seven three-level control factors.

To run the 18 experiments (as defined in the L18 orthogonal array) it was necessary to design 18 different CAD models (shown in Fig. 5a). The students designed CAD models based on the control factors and added a hook on each model for testing purposes as well as approximating an assumed decoration.

Table 1. Values of control factors and noise factors for Case Study A experiments.

Factor	Description	1	2	3
A	3D printing material	PLA	ABS	
B	Speed	Low	Medium	High
C	Pulling angle	30°	60°	90°
D	Thickness of upper layer	0.5 mm	1 mm	5 mm
E	Contact part area	1 mm	2.25 mm	4 mm
F	Contact part gap	0.5 mm	0.7 mm	1 mm
G	Height of contact part	0.5 mm	1 mm	1.5 mm
H	Contact part shape	Circle	Square	Triangle

After finishing the CAD models, they needed to be 3D printed. There were several problems that appeared. Second the fabric needed to be prepared carefully and flattened onto the bed of the 3D printer, a method with tape was used to achieve this (Fig. 5b). Finally, although the PLA based models printed very well (shown in Fig. 5c), the models based on ABS material had problems to adhere to the fabric and were therefore rejected. After 3D printing the models, the experiment was executed by attaching a force gauge on the hook of the 3D printed model (shown in Fig. 5d). Based on the experiments defined in the array, the force gauge was then pulled from one of the different directions until the 3D print separated from the fabric.

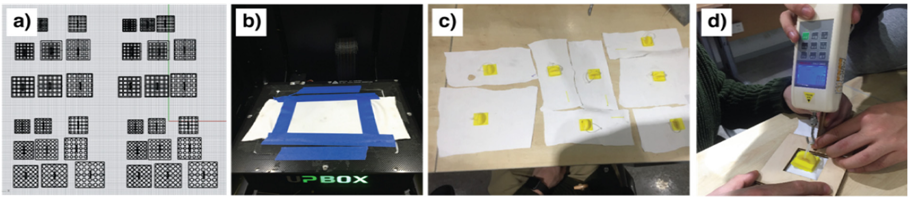

Fig. 5. Overview of the steps executed during the experiments of Case Study A.

4.2 Experiment Case Study B

In order to optimize the pressure on the head, five control factors and one noise factor, with two levels were taken into account (shown in Table 2). Based on this structure, L16 was chosen as the orthogonal array. Eight CAD models of the air chambers were 3D printed based on the parameters defined in the L16 orthogonal array (two CAD models are shown in Fig. 6a). Before the printing step, the fabric was fixed on the base of 3D printer (Fig. 6b). The air chambers were printed on an elastic polyester fabric which had good adhesion to the 3D printing filament (three out of eight of the models are shown in Fig. 6c). To control the air intake volume and control the intake speed, a 70 mL injection syringe was used to deliver gas at an injecting speed of 15($\pm$1) mL/s. The injector was connected to one end of a tube, while the other end of the tube was covered by a balloon. The pneumatic parts, including the 3D printed air chamber model and the balloon bonded with the tube, could be fixed on the inside of the hat by sewing the fabric and cap together (as shown in Fig. 6d). The material of the cap used in the experiment was wool and had a radial elastic coefficient of 233.33 N/m.

Table 2. Values of control factors and noise factors for Case Study B experiments.

Factor	Description	1	2
A	3D printing material	ABS	PLA
B	Bottom contact base	3D Printed	Fabric
C	Bottom area/height ratio	Small	Large
D	Air intake volume	20 mmL	40 mL
E	Hat tightness	Tight	Loose
F	Hair density	Thick	Thin

For the testing device, a polystyrene foam board was shaped into the form of head and the dynamometer was embedded into the foam board to measure the force of the pressure on head, as shown in Fig. 6e. During the experiment, the balloon was inflated using the syringe, consequently the sensor on the dynamometer measured and recorded the peak value of the force (Fig. 6f). This value would be equivalent to the massaging force applied onto the head. Each 3D printed air chamber model was removed after the procedure was completed, and the next model was sewn on the cap. Each experiment was repeated with 5 replicates to calculate the average value, in order to come to a more accurate result.

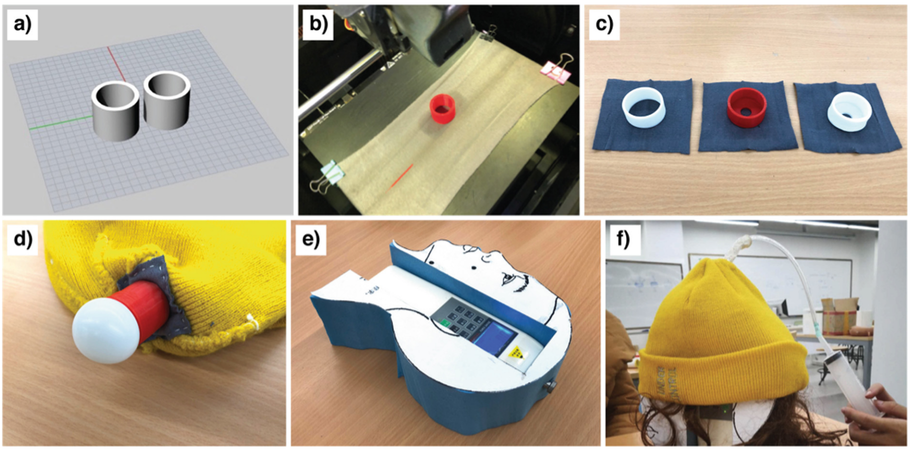

Fig. 6. Overview of the steps executed during the experiments of Case Study B.

5 Results

An important element of Robust Design Methodology is to observe control-by-noise interactions. Improved robustness can be achieved by selecting values of the control factors in such a way that the response becomes insensitive to the values taken by the noise factors [14]. Data analysis of these control-by-noise interactions can be carried out in different ways, analytically and graphically. These case studies utilized the factor-effect plot for the analysis.

5.1 Results Case Study A

As a first step, the test results were integrated by an ANOM analysis in order to gain information about the effect of the interaction between each control factor with each noise factors. Because the prints of the ABS filaments failed, the noise Factor A (printing material) was not taken into consideration. Then, based on the data of the ANOM analysis, the control-by-noise interactions and control factor main effect plots were drawn (shown in Fig. 7).

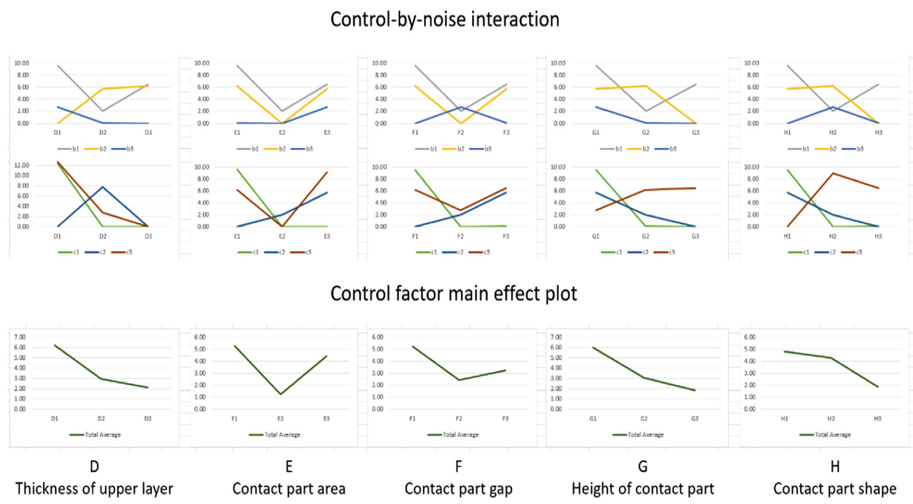

Fig. 7. Plots for Case Study A. The first line of the control-by-noise interaction plots visualizes the interaction of the noise factor B (speed) with the control factors. The second line of graphs shows the interaction between the noise factor C (pulling angle) and the control factor.

Considering both printing speed and pulling angle, for Factor D (thickness of upper layer) and Factor H (contact part shape), there was not a clear interaction among each line shown in the control-by-noise interaction. For factor E (contact part area), there is an intersection for both noise factors at level 2; however, the average line is not flat and level 2 is in the lowest point. Compared to these three, factor F (contact part gap) and factor G (height of contact part) are relatively suitable for controlling robustness. As shown in the Fig. 7, the chart of factor F is similar to the factor E in that the interaction occurs in the middle for pulling speed and for level 2 and 3 for pulling angle, but the average line is flatter, and the lowest point is also higher. For factor G, the intersection occurs on the point between level 1 and level 2 for pulling angle, which is also a comparatively high position of the average line. Finally, factor F and factor G will be selected to control the robustness. The target response is the highest pulling strength. The level of the other factors were chosen at the highest point of its average line, which are D1, E1 and H1. Based on the previous analysis, the selected values were applied to the design (Table 3), a new CAD model was created (Fig. 9a), 3D printed and tested (shown in Fig. 9b). After multiple printing tests and removing an outlier value with a much higher adhesion, the results were 121 N, 60 N and 84 N. These values are significantly higher than in the first round.

Table 3. Selected values for the improved design of Case Study A.

Factor	D	E	F	G	H
Level	0.5 mm	1 mm	0.7 mm	0.5 mm	Circle

5.2 Results Case Study B

In total, there were 16 groups of experiments with 5 replicas. After the test, the raw data was converted into plots to visualize the control-by-noise interactions and the control factor main effects plot (shown in Fig. 8). For Factor A (3D printing material) it can be seen in the first plot that it has highest robustness when printing with the hard ABS filament. However, practically the softer material enabled the components to be printed with higher accuracy and better attach to the fabric. The plot of Factor B (Bottom contact base) shows that when the printing component has a hard base instead of the fabric, it will result in increased robustness because the two lines for thick and thin hair intersect on the left. Factor C (Bottom area height ratio), shows the maximal robustness

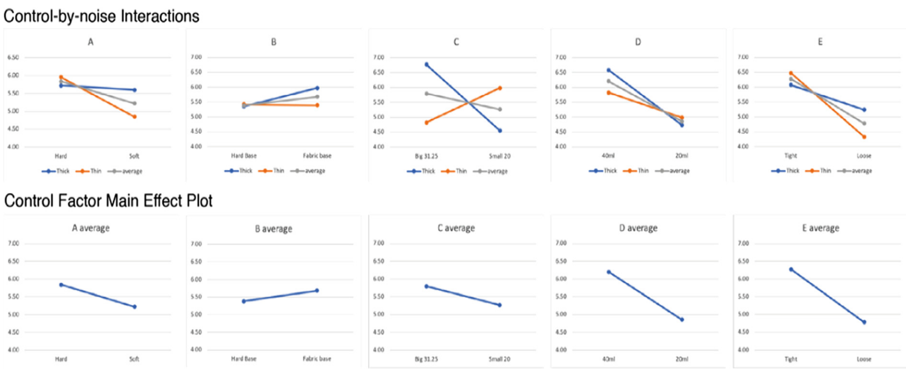

Fig. 8. Plots for Case Study B. The control-by-noise interaction plots show the interaction between the noise factor F with the individual control factors.

of the system can be achieved when the ratio is at the half-way point between the minimal and maximal value. Therefore, a middle point of 24.77 mm was selected. Factor D (air intake volume) was used as a scaling factor that could be adjusted based on the outcome of the other control factors. After adjusting the other factors, the sum of the prediction was 6.4 N, exceeding the target by 0.4 N. By calculation, an air volume of 32.56 mL would change the force to 6 N. For the tightness of the cap (Factor E) the plot shows that the tighter the hat is, the higher the robustness of the product. So the level of "tight" was selected for improve robustness.

Finally, a confirmation experiment was conducted with a 3D printed model (shown in Fig. 9c) developed according to the factors that resulted from the analysis. The response of the confirmation experiment was very close to the target value of 6 N. However, the variance was greater than previous experiments, and the response was unstable. The students hypothesized that during the injection of air into the balloon, the expansion is larger than the gap between the scalp and the 3D printed air chamber, which resulted in some measurement errors. In order to improve the unstable expansion direction of the balloon, a thin film was made with silica gel and attached to the edge of the 3D printed air chamber (Fig. 9d). The silica gel film could effectively restrict the direction of balloon expansion and accurately apply pressure to the specific acupoint. Therefore, the students concluded that their conjecture that the large variance of data is mainly due to the difficulty of controlling the direction of balloon expansion was correct.

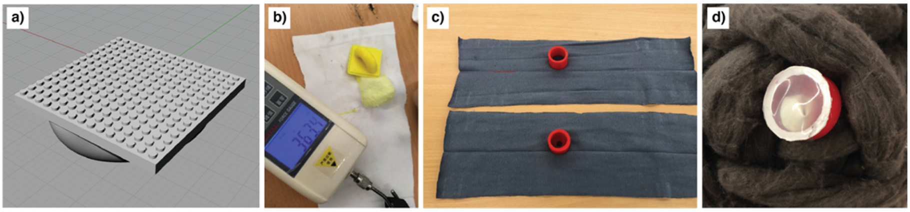

Fig. 9. Figures of the validation tests performed with the selected factors for both case studies.

6 Conclusions

In this article, the authors present the application of Robust Design methodology to two case studies that use 3D printing on fabric to enhance the capabilities of the fabric. The goal of this article was not to develop a set of design parameters that could be used by designers to 3D print on fabric. Rather, the authors intend to illustrate a method which can be used by designers to optimize the functionality of their 3D printing application. Of course, during the process some general insights could be realized, for example, in both projects the use of polyester was preferred over other fabric types, and the use of soft PLA filament worked better than the harder ABS variant.

For both case studies we found that Robust Design techniques helped to determine the optimal parameters for the target response that we were pursuing. In Case Study A, the adhesion exceeded our expectations since it resulted in a much stronger connection compared to the preliminary experiments. In Case Study B, the final pressure exerted by the pneumatic actuator could be precisely matched to the target response needed for the acupoint pressure massage. Moreover, Robust Design techniques can be useful in scenarios where designers do not have full control over all the parameters because Noise factors can be explicitly taken into account. For example, when people would like to 3D print functionalities on top of their own clothing, the material the user selects could vary. Likewise, when wearable applications have to be personalized to people's preferences and physical characteristics (such as the location of acupressure points or the thickness of the hair underneath a cap), the thickness of hair would vary between users.

Since these case studies took place in an educational setting as part of a course to teach about Robust Design methodologies, the time period that was available was rather short. Even in a project of short duration, the students managed to achieve results which improved the final products.

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