공학석사학위논문

Design and manufacture of custom-fit pillow in perspective of cervical spine pose maintenance

경추 자세 유지 관점에서의
맞춤형 베개 생산 및 설계

2019 년 8 월

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이 논문을 공학석사 학위논문으로 제출함

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이창민의 공학석사 학위논문을 인준함

2019 년 6 월

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Abstract

The advent of mass production led a better quality of life of human by providing a number of products to the public with satisfaction of demand for products. However, the demand for product considering each personal characteristics of user began to grow. This demand became satisfied as the development of manufacturing technology made the production cost of customized products cheaper. Especially, products such as shoes, jacket, trousers were custom-fitted and provided to customers nowadays with sophisticated analyses on each product. However, it is hard to custom-fit and manufacture the product. For some products, custom-fit design and production were not proposed with body data of the users even though analysis on the product were steadily studied.

In this research, based on studies on pillow, custom-fit pillow was designed and manufactured. First, head data was acquired by a commercial handheld scanner. With the acquired head data, pillow was designed to minimize the stress on the cervical spine by applying cervical curvature angle (CCA). Four design trials were taken to design appropriate custom-fit pillow for participant. In the first trial checked whether produced pillow supported to maintain cervical spine pose. Second trial controlled stiffness of pillow by changing lattice structure while producing pillow. In third, custom-fit pillow was designed considering not only supine position but also lateral position. Last trial solved the problem of third pillow by introducing new design process. By comparing head data of other subjects, it was proved that final design of the pillow fits well to original subject.

Using produced pillow based on final design also showed that actual pillow was also comfortable to use.

Keyword : custom-fit, pillow design, 3D printing

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Chapter 1. Introduction

With the advent of mass production, products such as necessities, garments and beddings were massively produced and supplied to public. Majority of products for public were classified by size such as height, waist, bust and hip. However, some study reports these mass-produced products were not satisfactory to customers due to different body shape of each customer [1][2]. The result of these studies imply the needs for custom-fit products.

The development on manufacturing technology enabled manufacturers to produce automated custom-fit products with computer-aided design (CAD) programs [3]. Researches about product including user assessment have accumulated and become more sophisticated with the needs for more customized fits. Moreover, digitalized data became more accessible with advancement of scanning technology. These advancements led the paradigm of mass customization, where customized products are available at a cost lower than traditionally customized products [4]. Compare to standard products, these customized products are more selected by customers [3].

On the other hand, researches about appropriate pillow design for human have steadily studied. Because sleep effects human's abilities such as immune system[5], emotion [6] and learning [7], comfortable pillow is needed in terms of high quality sleep. A study shows that usage of unsuitable pillow induces pain on cervical spine, which inhibits the satisfactory sleep quality [8]. While some factors such as infill material and temperature make pillow uncomfortable, it is suggested that the pillow geometry is the most influential factor determining comfortable pillow [9]. It is also asserted that the pillow shape maintaining cervical spine in the neutral position is the ideal pillow shape for human [10].

With improvement of rapid prototyping technology, printing large objects with a variety of materials including bronze, wood and polyurethane, has become possible by commercial 3D printers. If custom-fit pillow geometry is obtained based on digital data of an individual, then pillow can be produced by 3D printer with proper material. However, method to produce custom-fit pillow by data of an individual is still not proposed.

This research proposes a method about design of custom-fit pillow by maintaining cervical spine pose in order to minimize the pain on the neck by the head data of an individual. The overall progress is shown on Figure 1.1. First, head data is obtained by a commercial scanner and is post-processed. Pillow geometry is then created based on head data by proper criteria with study about pillows. Finally, created custom-fit pillow is produced by 3D printer.

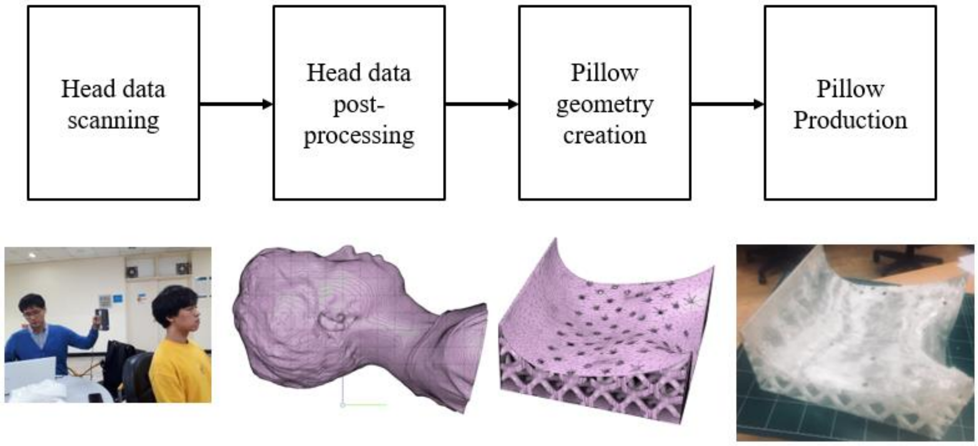


Figure 1.1 Overall progress

Chapter 2. Related works

2.1. Custom-fit

Research about custom-fit products have conducted in varieties of products. Jackets were custom-fitted for ten participants and it was found that seven were satisfied with custom-fit designed jacket [3]. Rout introduces a process to generate custom shoe last geometry by measurement devices with CAD program [11]. Custom-made pants were also suggested by classifying body shape of subjects and changing each design of pants with respect to classified body shape [12]. Design of pillow was also suggested with head data classified according to the head shape [13].

2.2. Pillow analysis

To design custom-fit pillow, researches such as comfort or pain analysis about pillows should be considered to design appropriate custom-fit pillow for individual. One study shows that neck support, pillow temperature and pillow comfort is crucial for suitable pillow, and analyzed the effect of these elements [14]. Another study evaluated three different pillows by subjects with neck pain and showed that appropriate pillow selection relieved the pain [15]. Other study simulated the effect of pillow height on neck pain with finite element analysis [16]. In addition, rubber material was strongly recommended as material of pillow by analyzing 6 different pillows in perspective of sleep quality [17].

Anthropometric analysis regarding pillow is also crucial to design custom-fit pillow. Cai measured 40 subjects in the natural standing and suggested proper pillow design regarding the measurements in the study [18]. Relationship between contact pressure and cervical curvature angle (CCA) of subject is analyzed for designing optimal pillow [19]. Another study measured shape of back of the head and neck (SBHN) to design comfortable pillows [20].

Chapter 3. System specification

This chapter covers the system used for manufacturing and designing custom-fit pillow.

Scanning system is required to obtain subject's head data in order to design custom-fit pillow which follows subject's head shape. The data will be processed at Chapter 4. If scanning is done, pillow is designed with the method which will be covered at further chapters. When custom-fit pillow geometry data is obtained by the procedures, it should be produced to test the pillow which requires manufacturing system. At Chapter 5, the test pillow is produced by the manufacturing system introduced on this chapter.

3.1. Head scanning system

To scan head data of a participant, a commercial handheld 3D scanner is used. In this research, Sense 3D scanner by 3D systems is used to obtain subject's head data [21].

The scanner uses infrared projector to obtain the mesh of the object. It saves the scanned result into mesh data format such as STL file format or OBJ file format which will be processed on this research.

Figure 3.1 Sense Scanner

3.2. Pillow manufacturing system

3.2.1. Material

In this research, thermoplastic polyurethane (TPU) is used as material for pillow because a comparative study showed that rubber material pillow has effect on good sleep quality and good comfort [17]. This research uses TPU material filament produced by eSUN [22].

Figure 3.2 eSUN 3D FILAMENT eFlex Natural

3.2.2. Hardware

In order to manufacture custom-fit pillow for a subject, this research used a FDM type additive manufacturing system. Sindoh 7x is used to produce designed custom-fit pillow [23]. This FDM type 3D printer supports filaments not only PLA or ABS material but also other materials such as copper, wood, TPU materials.

Figure 3.3 Sindoh 7x

3.2.3. Software

In order to make cushioned pillow with obtained pillow geometry, software supporting infill generation with variety structure and perforation is needed. Autodesk Netfabb 2019 is used in this research, which supports generating lattice structure inside of the pillow geometry to make produced custom-fit pillow more cushioned [24]. Autodesk Fusion 360 is also used as design tool to generate pillow geometry for this research [25].

Chapter 4. Head data preparation

This chapter describes acquisition and processing head data which is obtained by scanning system described at Chapter 3. A study shows that the head data obtained by hand-held scanner is close to the head data obtained by standard method using CT or MRI. This justifies the usage of handheld scanner as head data acquiring tool [26].

To build a process of designing custom-fit pillow for a subject, it is necessary to acquire the subject’s head data and its corresponding feature points. Then, the acquired head data is decimated and smoothed in order to make the head data close to traditionally scanned head data. With feature points extracted from the head data, the head data is aligned to pillow design coordinate by matching the feature points in order to design the custom-fit pillow on Chapter 5.

4.1. Acquisition of head data

With scanner introduced on Chapter 3.1, subjects were asked to sit on the chair in natural position. Then scanner scans the subject's head data. This process is shown on figure 4.1 (a) If the scanner finishes scanning, obtained head data is saved into a mesh data as shown on figure 4.1 (b).

(a)

(b)

Figure 4.1 (a) Scanning process (b) Acquired head data

4.2. Feature point extraction

To design the pillow based on scanned head data obtained from Chapter 4.1, feature points needs to be extracted from head data. Researches about the relationship between pillow geometry and feature points on head were previously conducted [19][20]. This research uses the Cervical Curvature Angle (CCA) [19] which considers cervical spine pose to determine relationship between head orientation and pillow. CCA is determined by the base line and the line connecting tragion point and shoulder tip point as shown on figure 4.2. To design custom-fit pillow, tragion point and shoulder tip point of both sides were extracted from head mesh data as feature points. These locations are shown on figure 4.3.

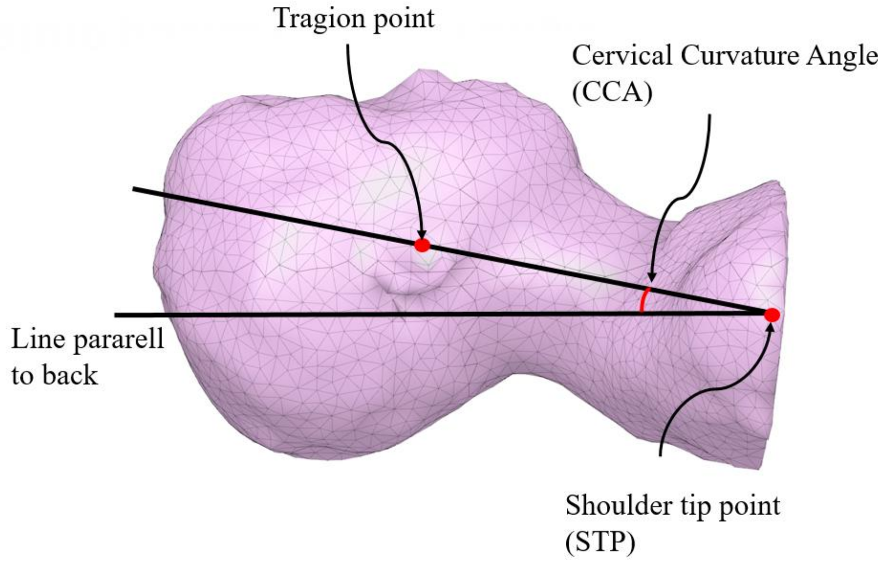


Figure 4.2 Illustration of CCA angle

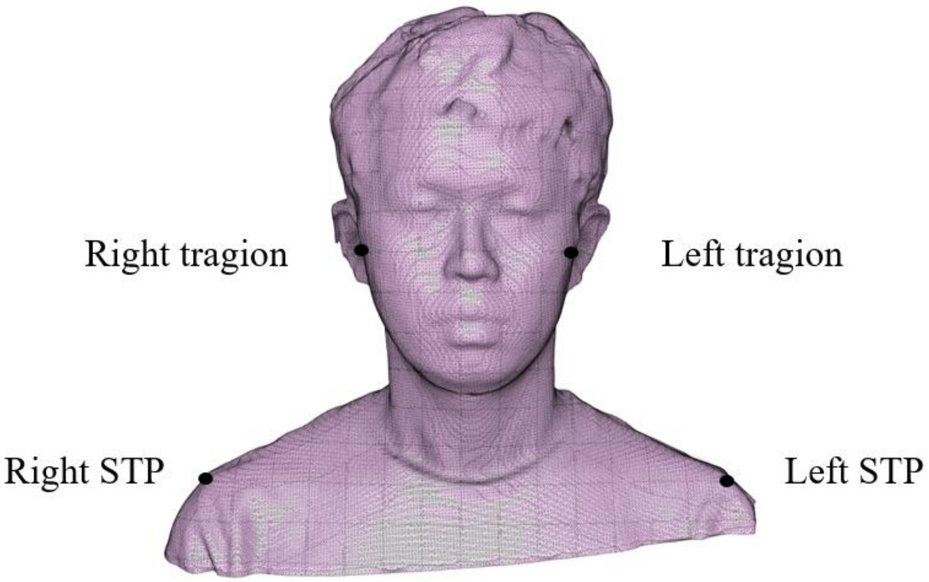


Figure 4.3 Feature points for pillow design

4.3. Head data post-processing

4.3.1. Decimation and smoothing

Obtained head mesh data had approximately 200,000 faces. To reduce the computational cost on further processes, decimation is applied on the obtained head data. Quadric edge collapse decimation is used in this research, reducing faces of mesh data to 10,000 faces.

Head data acquired from scanner system includes human hair which makes head geometry quite in accurate. Moreover, some noise occurs on the head data because the scanner acquires the head data by stitching depth images. These factors necessitate smoothing the head data to reduce noise.

With decimated head mesh data, Laplacian smoothing with C2 continuity is applied. Assuming individual has shortcut hairstyle, smoothed head mesh become close to skinned head. Decimated and smoothed head data and its comparison is shown on figure 4.4 and figure 4.5.

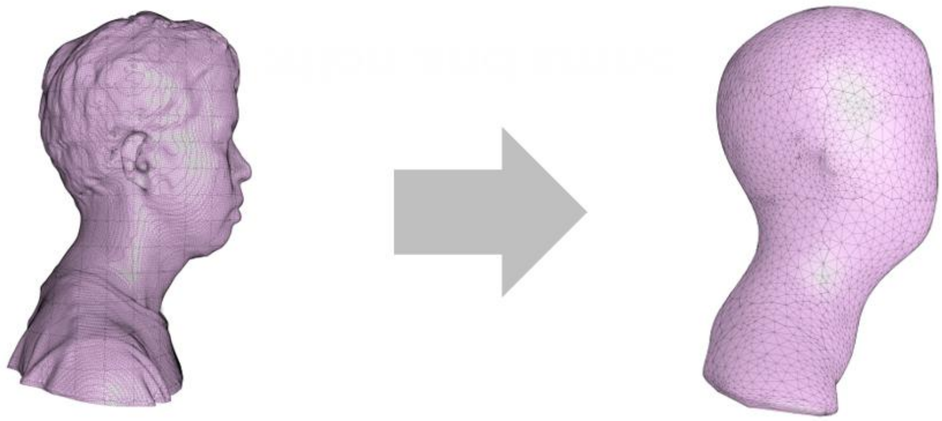


Figure 4.4 Decimated and smoothed head data

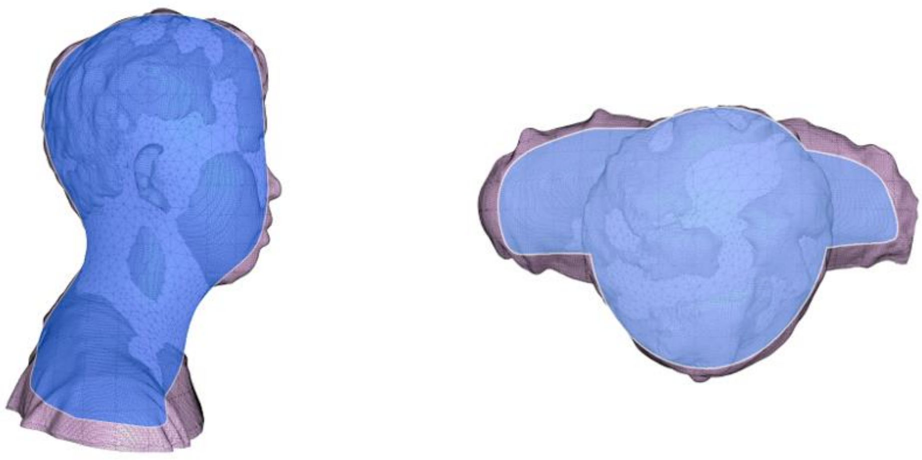


Figure 4.5 Comparison of original head data and post-processed head data

4.3.2. Head data alignment

Head data should be aligned to pillow design coordinate in order to design custom-fit pillow for a subject based on head data of the subject. Because head data is saved with respect to scanner's coordinate frame. At Chapter 4.2, feature points were extracted from head mesh data considering CCA. To align the head data to pillow design coordinate, feature points regarding CCA should be determined in pillow design coordinate.

To determine the feature points on pillow coordinate based on CCA, assume the floor is on XY plane where z = 0 and head is looking up to positive z direction. The lines connecting two tragion points and two shoulder tip points respectively should be parallel to XY plane. Assume YZ plane divides right and left head. This implies previously obtained two lines are perpendicular to YZ plane and YZ plane halves these lines. The procedure is illustrated on figure 4.6.

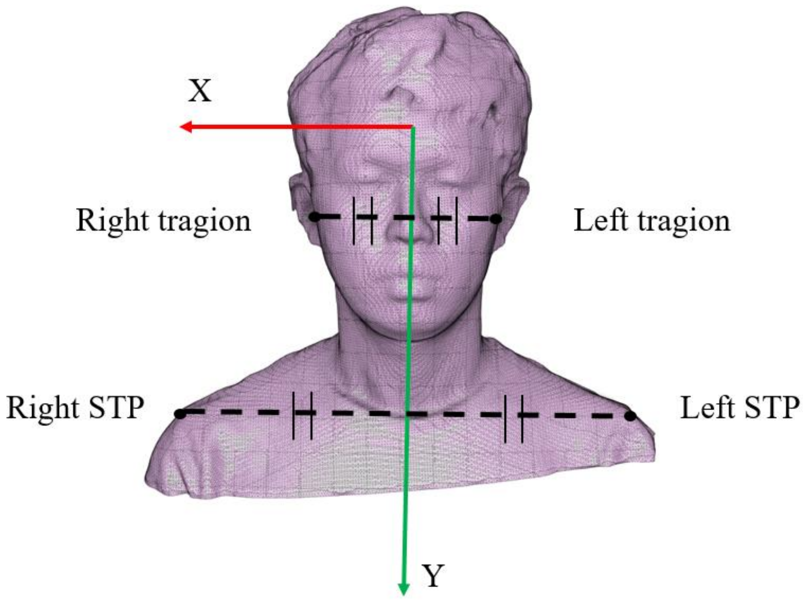


Figure 4.6 Relation of pillow design coordinate and feature points

Set the line connecting two tragion points pierce Z axis as figure 4.7. From Cai's study [18], the height of tragion point was suggested as 150mm. Because standard deviation of tragion height is small from the study, this value is used in this research although the value indicates the average of the subjects.

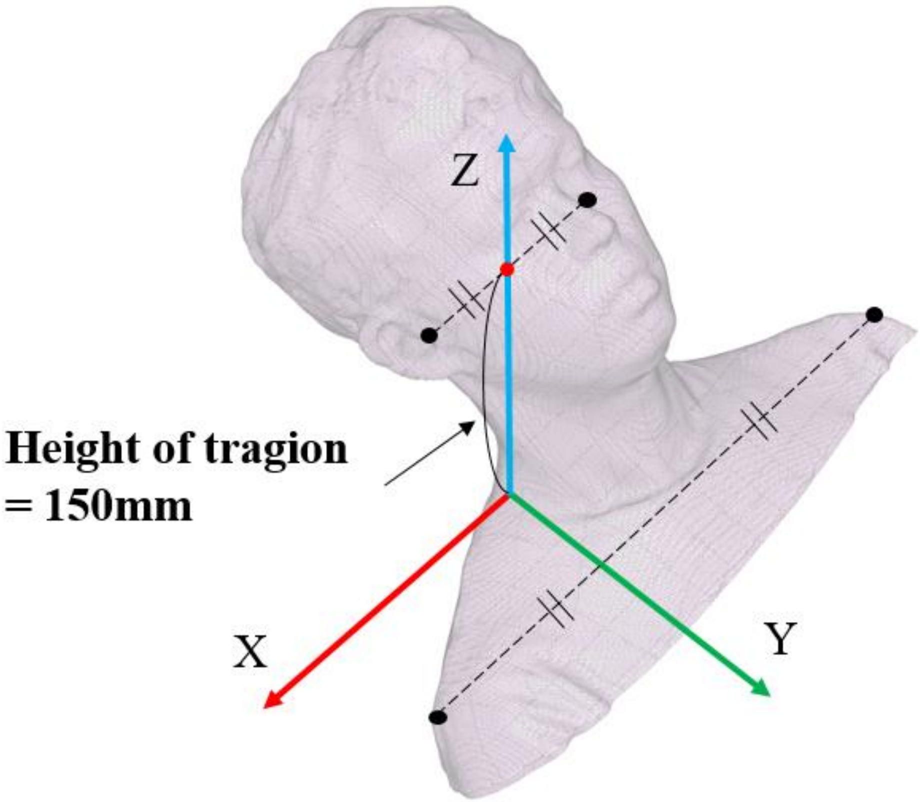


Figure 4.7 Tragion height decision and Z axis matching

Finally, CCA angle is applied between two lines. The value of CCA is determined as 20 degrees, which is similar to cotton pillow suggested by Kim [19]. Fully defined feature points on pillow design coordinate is shown on figure 4.8.

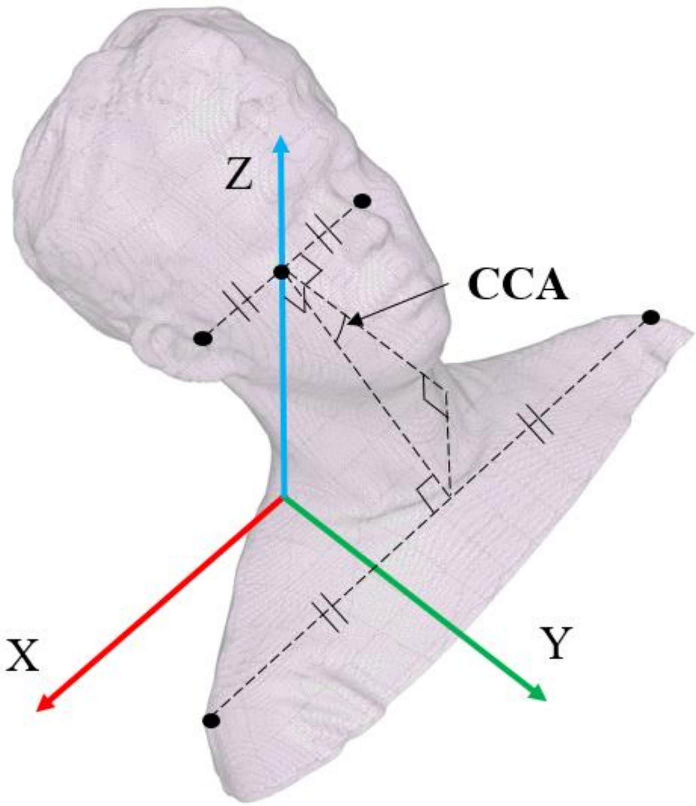


Figure 4.8 Fully defined feature points by applying CCA

With singular value decomposition method [27], feature points on head data are aligned to defined feature points on pillow coordinate. The process is illustrated on figure 4.9. Result of head data alignment to pillow design coordinate is shown on figure 4.10.

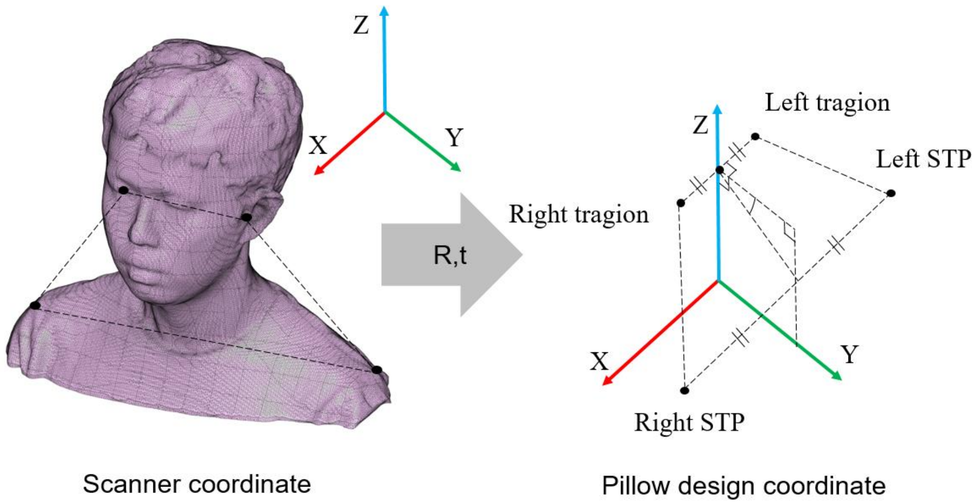


Figure 4.9 Overview of head alignment

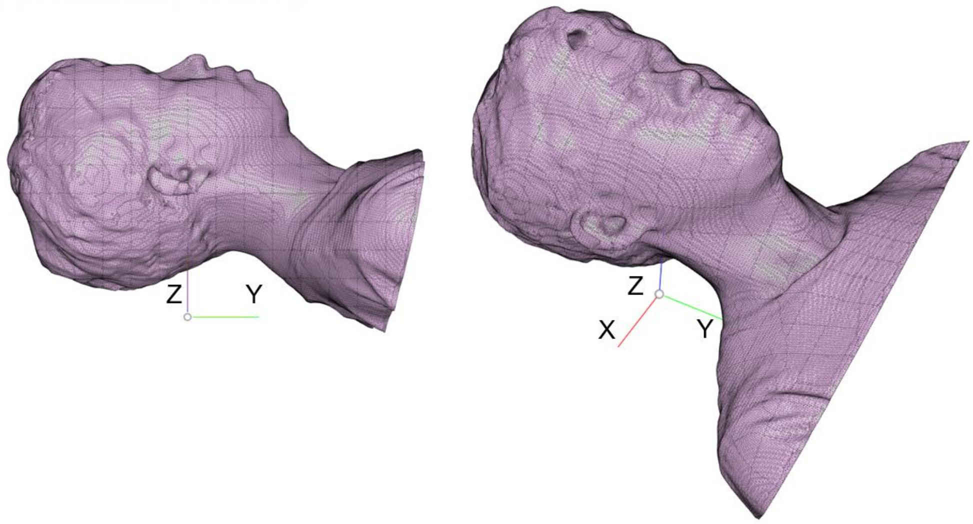


Figure 4.10 Result of head alignment to pillow design coordinate

Chapter 5. Pillow design

From Chapter 4, head data is aligned to pillow design coordinate with designated feature point position. With aligned head data, this chapter proposes the custom-fit pillow design method.

Goal of the design for custom-fit pillow in this research is to design comfortable pillow while maintaining the cervical spine pose as suggested on Chapter 4.2. To achieve the goal, this research designed the custom-fit pillow by following steps. First, referring the aligned head data, desired pillow sketch is drawn on YZ plane. Then, this sketch is extruded with some extent. Boolean operation is applied to this extruded model by aligned head data. The model applied Boolean operation becomes final custom-fit pillow geometry. This process is depicted on figure 5.1.

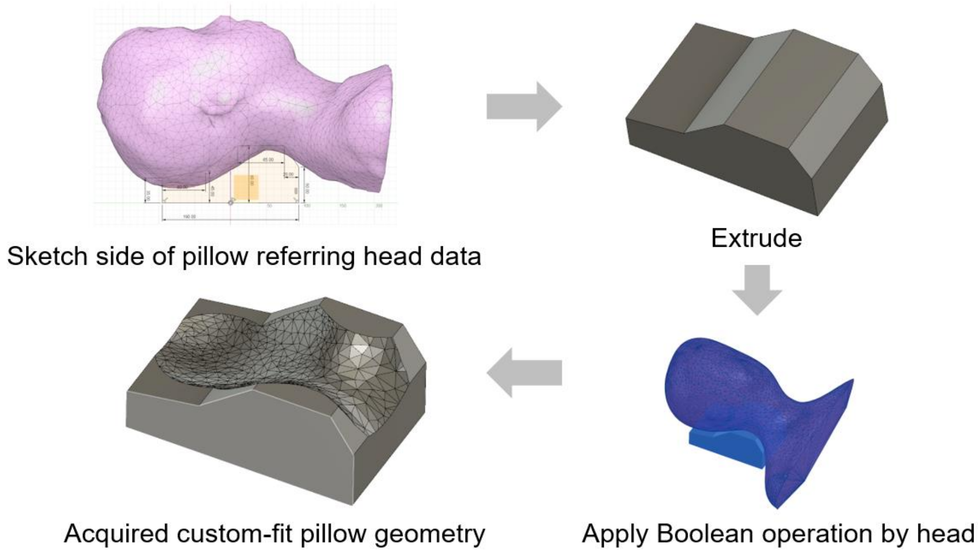


Figure 5.1 Overall process of pillow design

With acquired model, custom-fit pillow is produced by 3D printer introduced on Chapter 3.2.2. The subject used the produced pillow for 5 minutes and then gave feedbacks about the pillow. Design is then modified with the feedbacks from the subject.

5.1. First design

The first design of custom-fit pillow aims to check whether obtained pillow geometry really fits the head. To check this, side sketch of first design follows back neck and head as shown on figure 5.2. Based on this sketch, custom-fit pillow geometry data becomes as figure 5.3. In producing process, Sindoh 3DWOX desktop is used to generate infill structure to make pillow more actual [28]. Figure 5.4 shows the usage of the program. Produced pillow by and comparison with a board marker is shown on figure 5.5. It took 26 hours to produce the pillow.

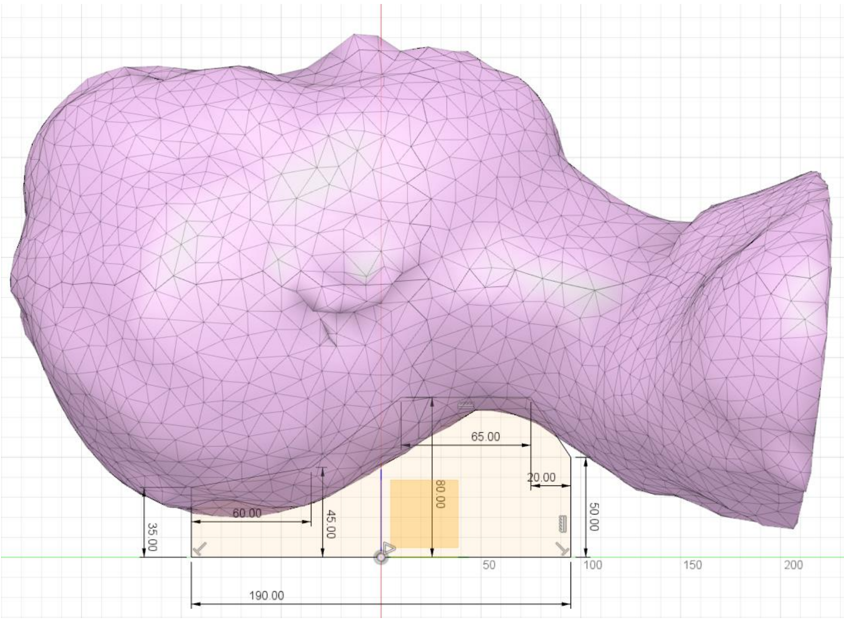


Figure 5.2 Side sketch of first design

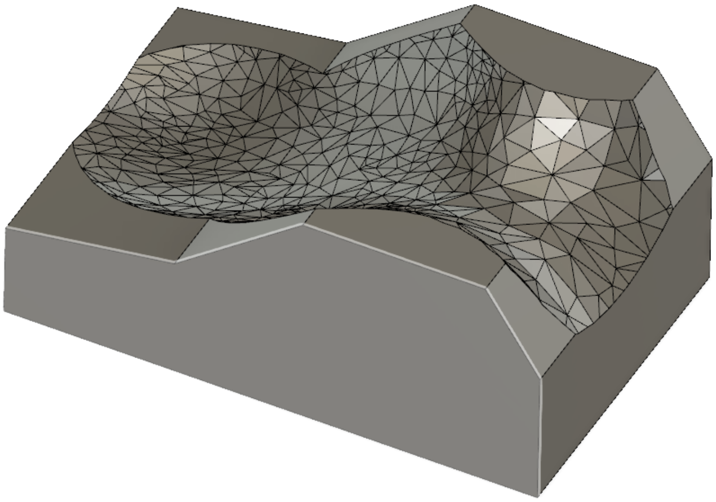


Figure 5.3 Acquired pillow geometry of first design

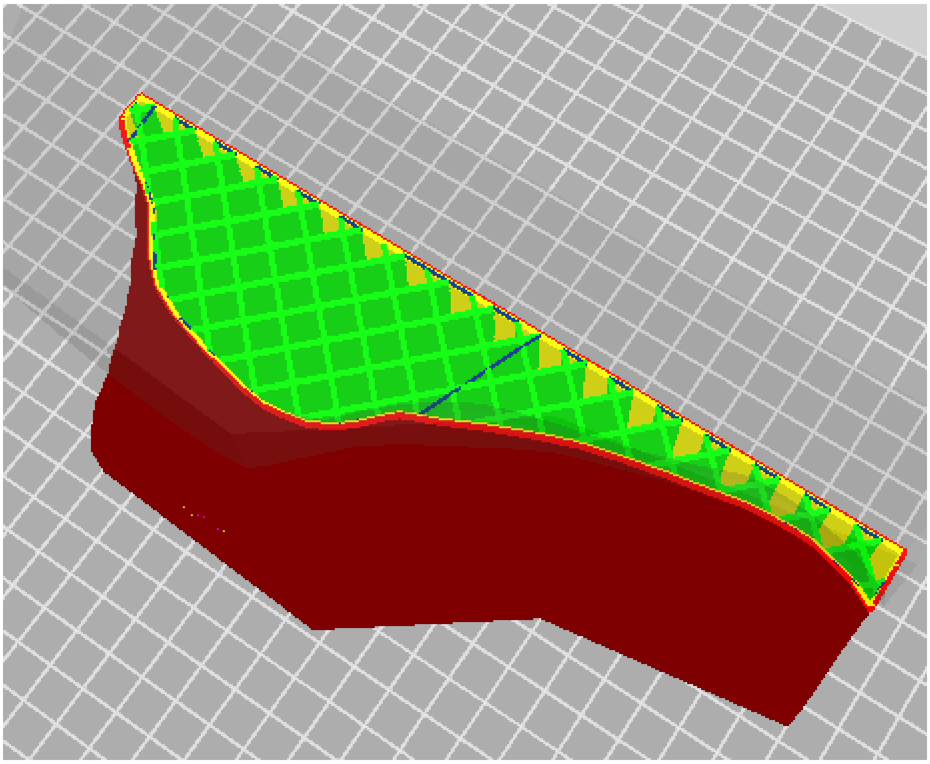


Figure 5.4 Usage of 3DWOX desktop and infill structure for first design

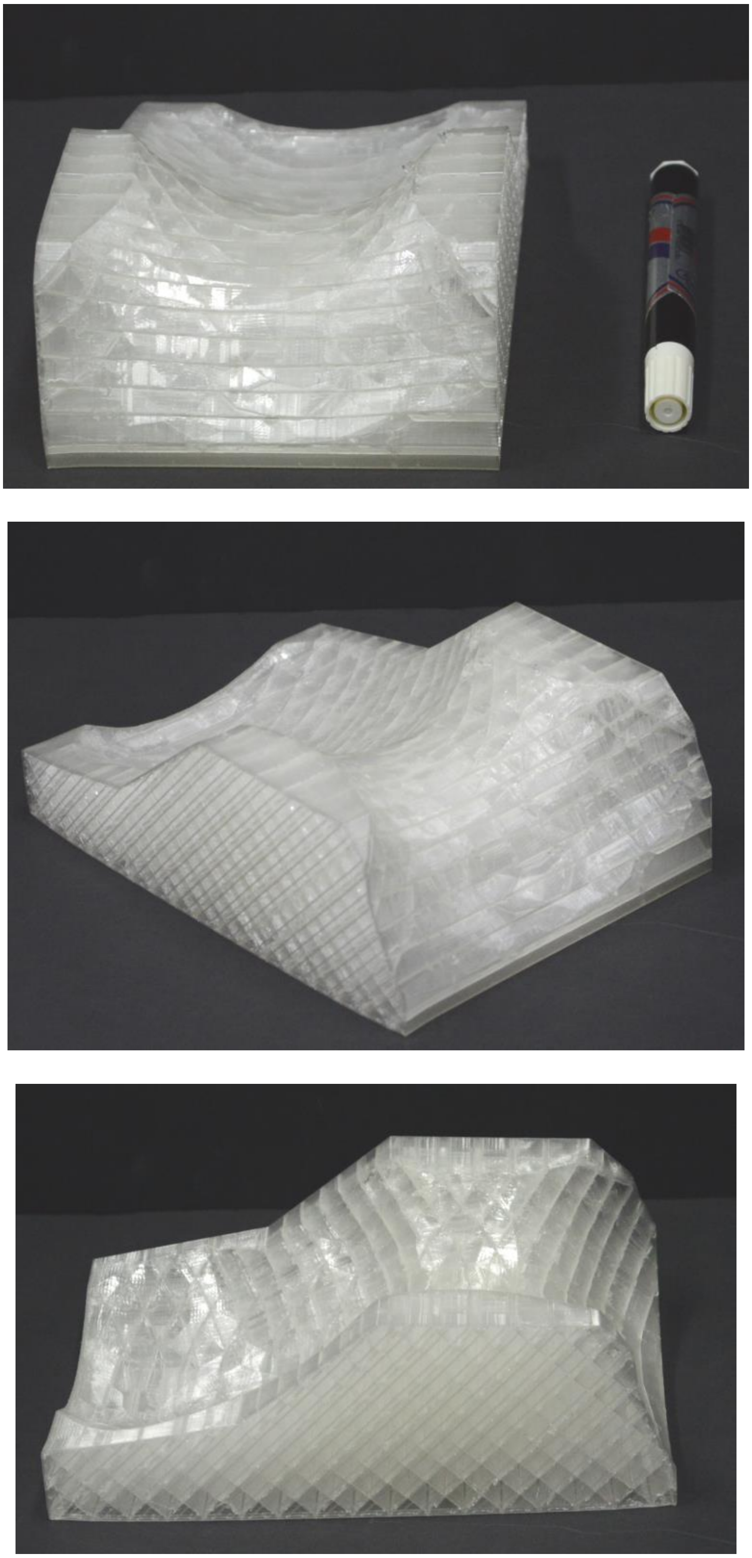


Figure 5.5 Produced pillow based on first design

After testing custom-fit pillow for 5 minutes, it was shown that the first designed custom-fit pillow somehow fits the head geometry of the subject. However, the subject appealed that pillow was too hard and was too small to use it. Airflow of pillow was also requested because subject claimed that temperature of the pillow increased over time.

5.2. Second design

The Second pillow aims to solve hardness of pillow and airflow problem proposed on first design. While maintaining geometry from first design, modification of infill structure and perforation on pillow geometry data is added by Audodesk Netfabb 2019 instead of using Sindoh 3DWOX desktop infill structure. Usage of program is shown on figure 5.6. To test variation of pillow hardness, two types of lattice structure, star and soft box which are supported by Netfabb, were used as infill structure to determine second design of pillow. Two results are shown on figure 5.7 and figure 5.8. It took 40 hours to produce each pillow respectively.

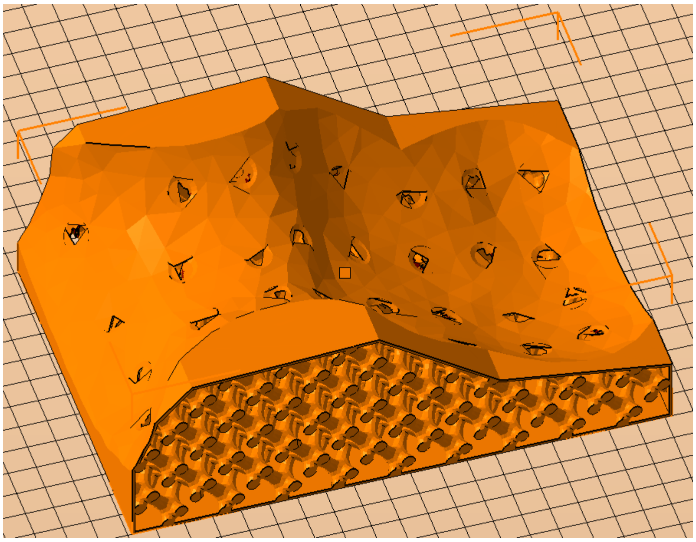


Figure 5.6 Infill and perforation added on first design by Autodesk Netfabb

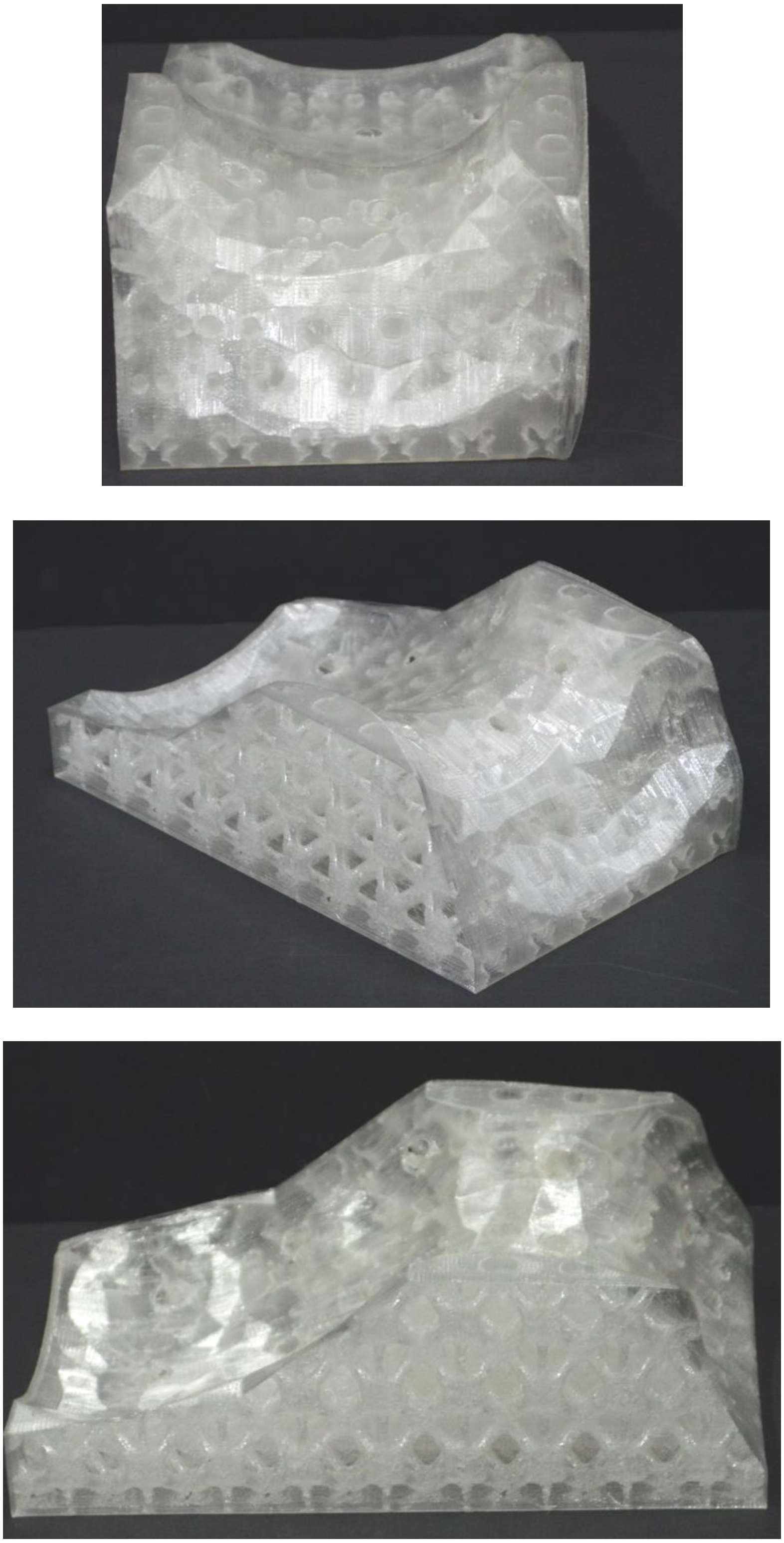


Figure 5.7 Produced pillow with star lattice structure

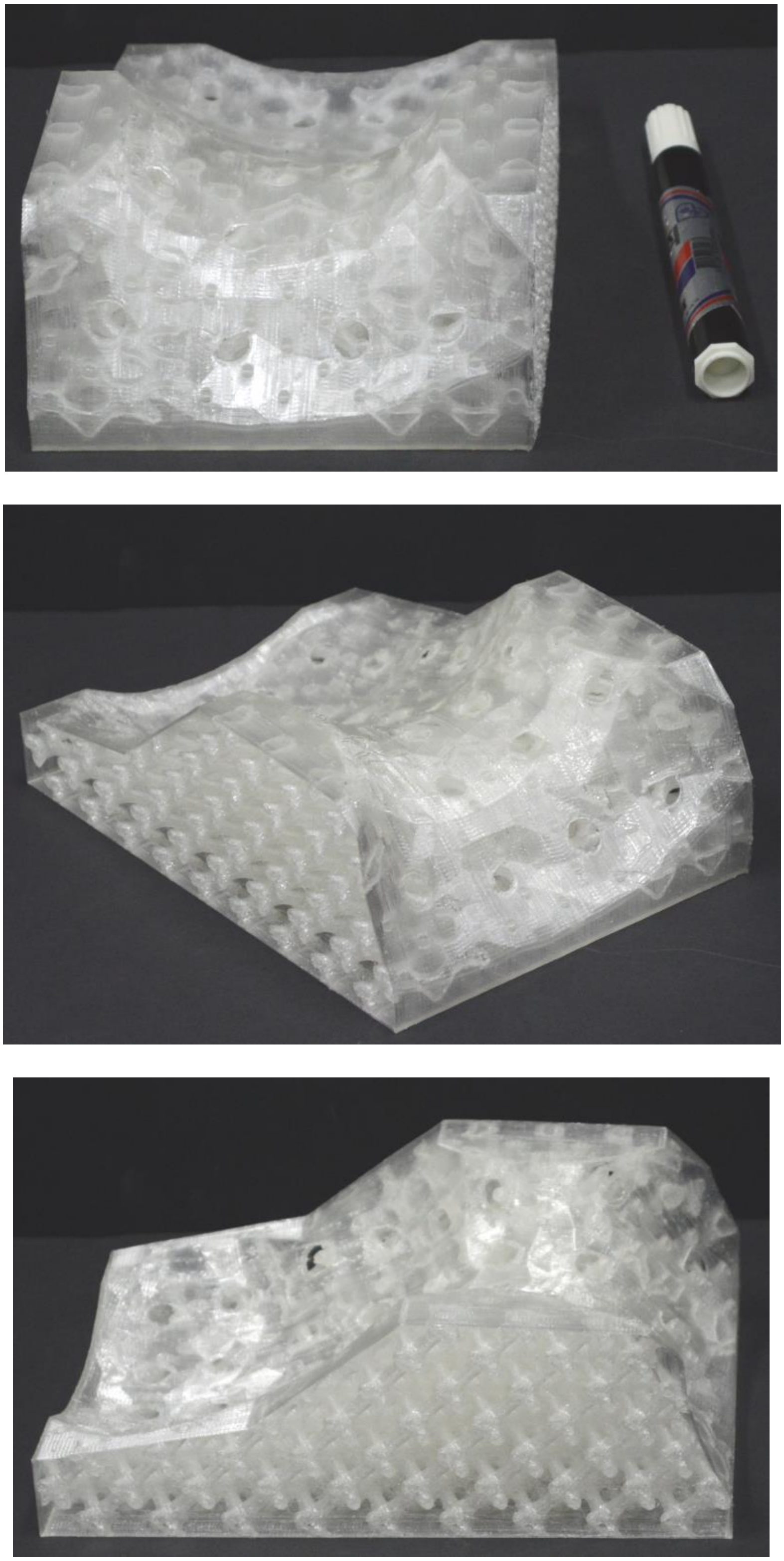


Figure 5.8 Produced pillow with soft box lattice structure

After using pillow, the subject gave feedback that perforation of pillow lowered the temperature of pillow which affects quality of sleep. It also turned out that two pillows from second design had different hardness. Compare to first design, infill with star structure was soft than first design while infill with soft box structure was harder than first design. Comparison of shape of each infill are shown on figure 5.9.

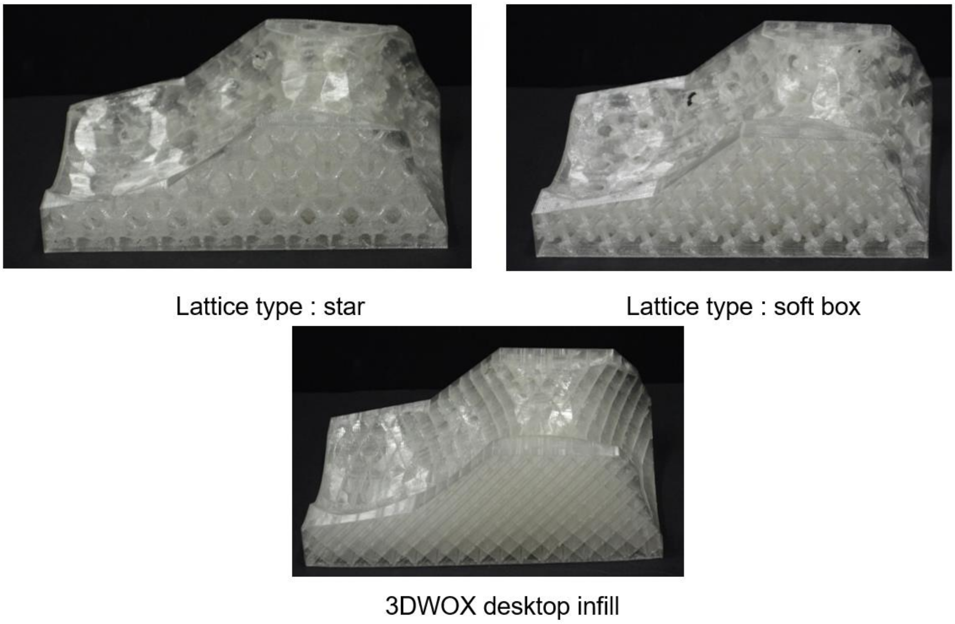


Figure 5.9 Comparison of infill structures

5.3. Third design

The first and second pillow designs verified that design of custom-fit pillow following head data fits to human and checked usability of custom-fit pillow. Feedbacks from first and second design solved some inconveniences and needs from subjects. However, the size of pillow was still not solved. Compare to average size of pillows on store, the first and second custom-pillows are relatively small.

The third design tries to make bigger custom-fit pillow which has similar size of a commercial pillow. By Cai [18], height of pillow should be different by the pose of human because human sleep in supine position for 60 percent and in lateral position for 40 percent while sleeping. This suggests that custom-fit pillow should consider these two positions. Because pillow design for supine position was already considered from previous two designs, design for lateral position should be covered at third design.

As shown on figure 5.10, third design covered the whole back head while first two designs just covered part of back head. Comparison between two designs is shown on figure 5.11. Extrusion of the sketch is also longer than first two designs. Pillow geometry of third design is shown on figure 5.12. W type lattice structure is applied to this design for more comfort. Final result of produced third design is shown on figure 5.13. It took 80 hours to produce the custom-fit pillow.

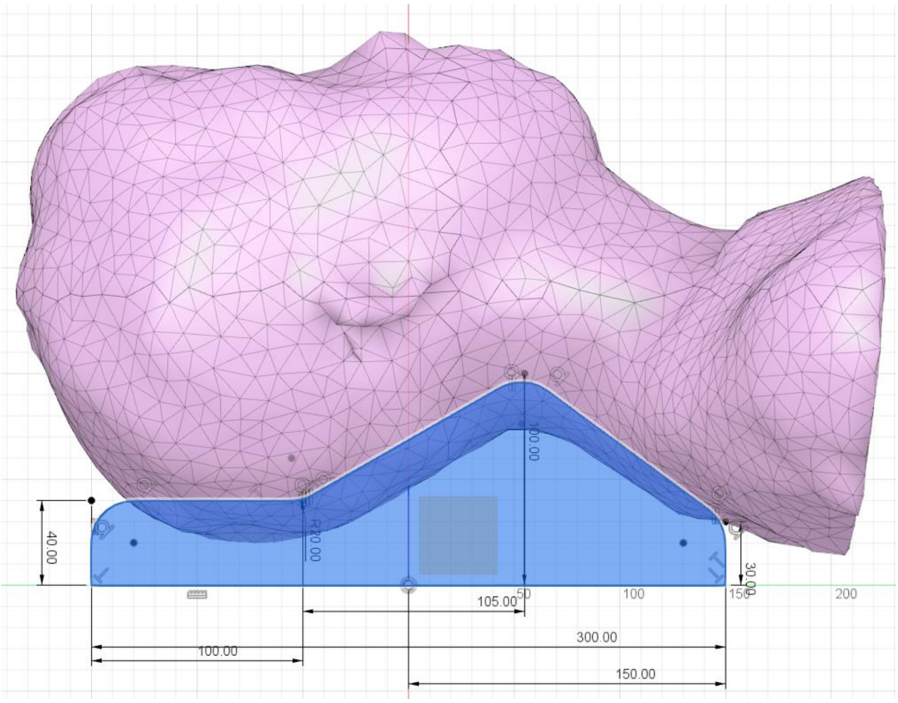


Figure 5.10 Side sketch of third design

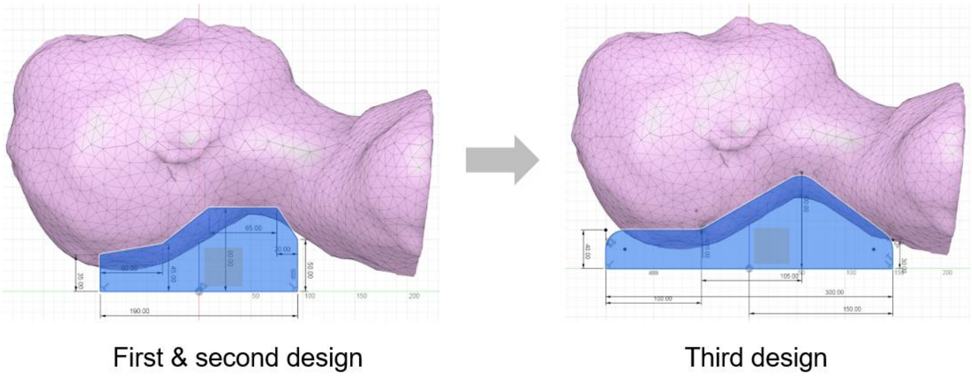


Figure 5.11 Comparison between previous design and third design

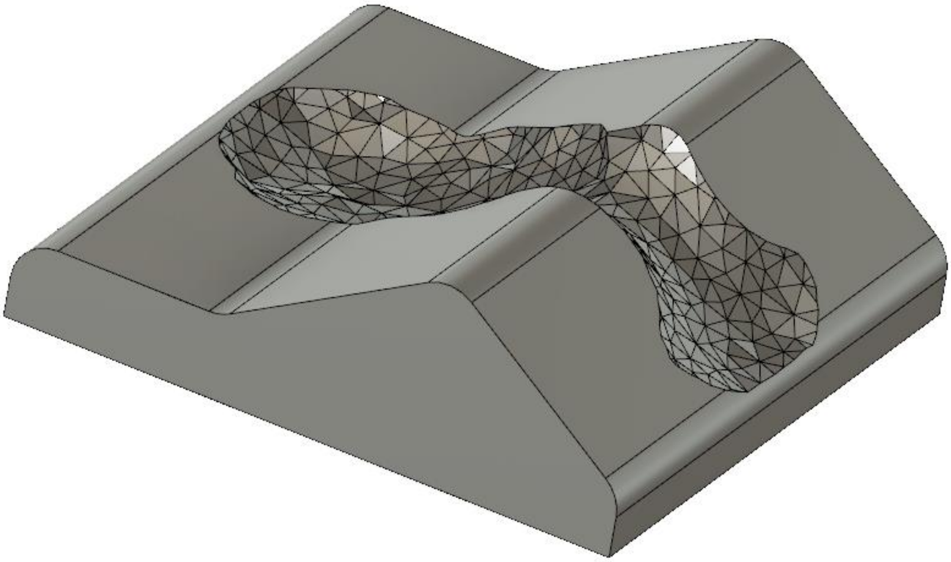


Figure 5.12 Acquired pillow geometry of third design

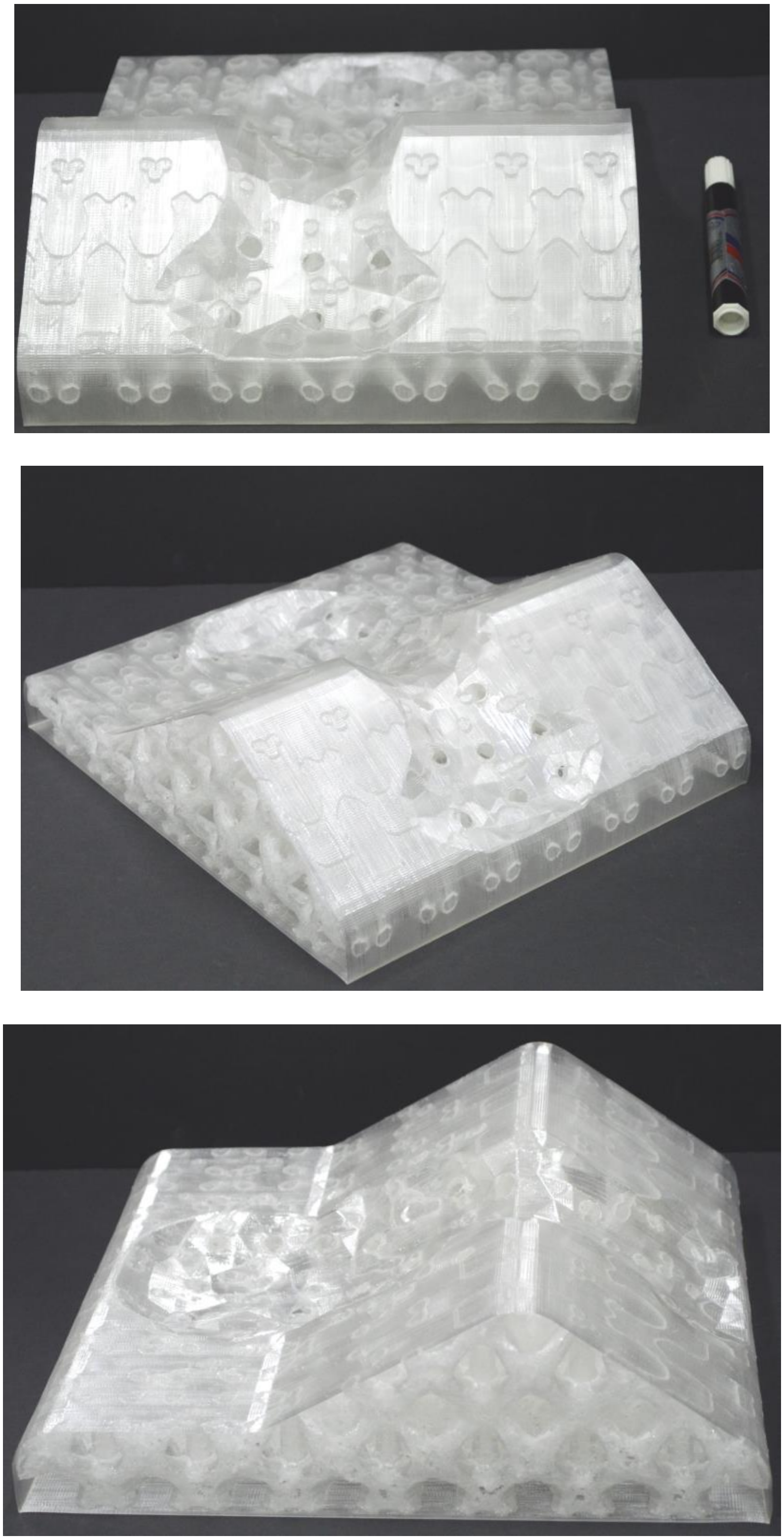


Figure 5.13 Produced pillow based on third design

Same as previous design tests, subject used pillow for 5 minutes and gave feedback. The subject insisted that the pillow was not comfortable due to pressure on the neck with deformation of pillow. It also turned out that using the pillow in lateral position was uncomfortable. Although the pillow design considered shift of posture, the subject claimed that moving head while using the designed custom-fit pillow was uncomfortable. The source of these inconveniences is assumed that designed pillow only considered height of pillow.

5.4. Fourth design

Third design failed to solve the problem of switching position and sleeping in lateral position. As mentioned at Chapter 5.3, main reason for inconvenience was previous design only considered height of lateral position. To solve this problem, considering head geometry for lateral position is needed.

In order to make custom-fit pillow consider supine position and lateral position smoothly, design method is changed in fourth design. As shown on the figure 5.14, instead of the method using extrusion on previous sketches, rotational sweep of sketch is adopted to cover head mesh data.

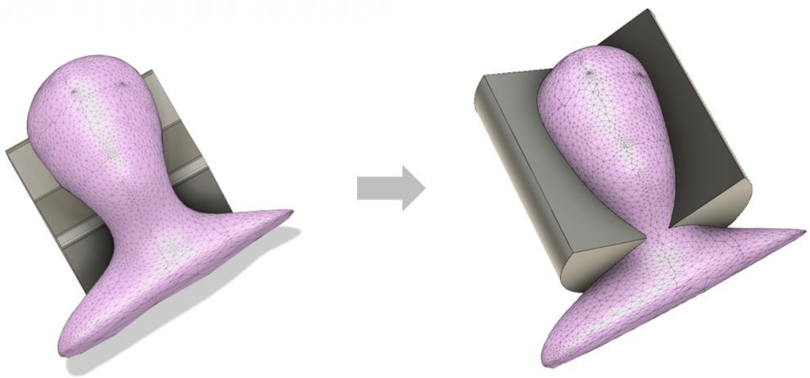


Figure 5.14 Change of base geometry generation

To make rotational sweep, it is important to select center axis of head to revolve the sketch. From the research of Luximon [29], the center of head is selected by midpoint of the two tragion points. At Chapter 4.2, we acquired two tragion points and aware of the position of these points. Then, line parallel to Y axis and piercing midpoint of two tragion points becomes rotation axis as shown on figure 5.15. This time, side sketch is just a rectangle covering whole head under rotation axis. The sketch is swept for 135 degrees by both sides. Then geometry which finished Boolean operation with head data is illustrated at figure 5.16.

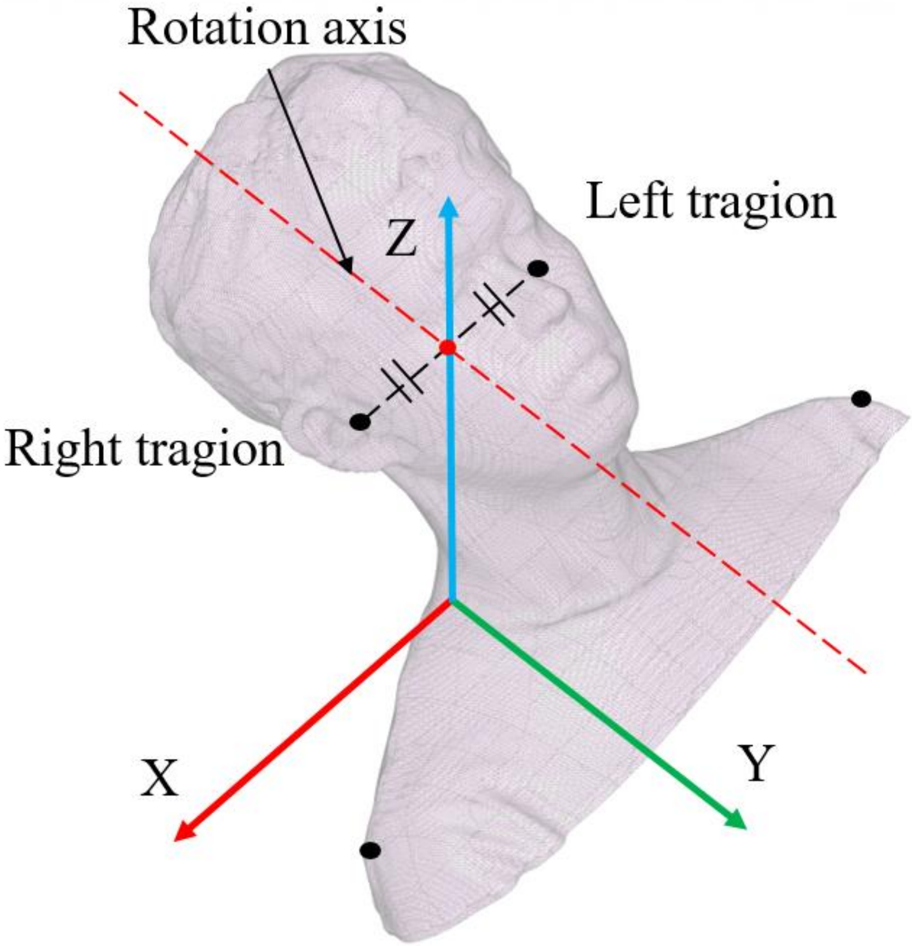


Figure 5.15 Illustration of rotation axis

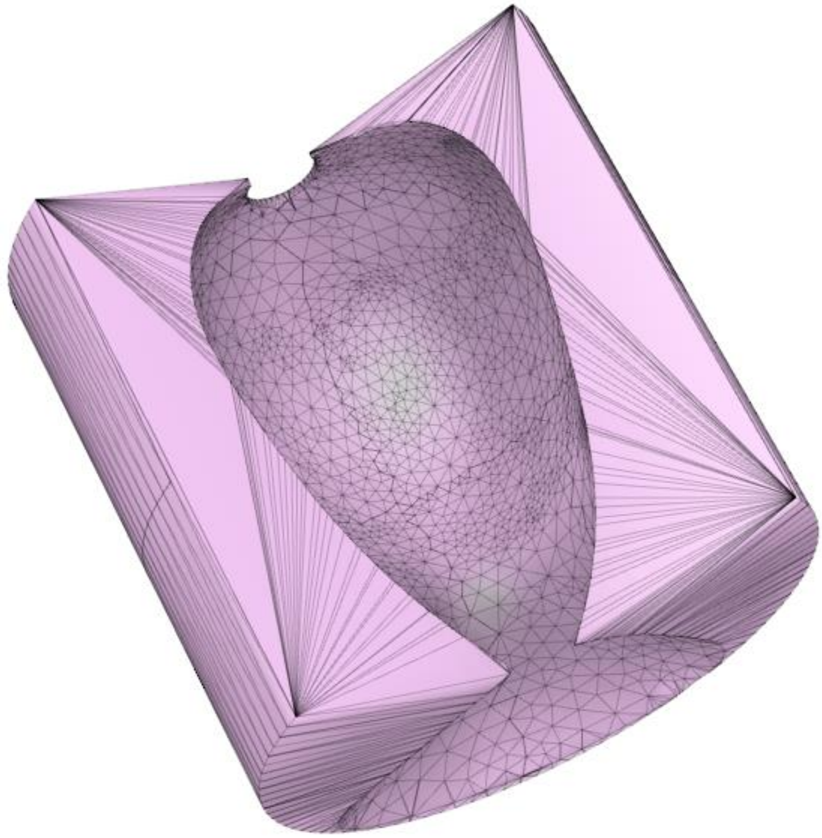


Figure 5.16 Acquired geometry data from changed base geometry

The geometry shown on figure 5.16 is far from the ordinary pillow in the market. To make this model as actual pillow geometry, it should be morphed into the extruded form like three previous custom-fit pillows. The meaning of the geometry morphing into the extruded model is the consideration of head rotation. In other words, morphed pillow geometry will cover supine and lateral position of the head. As the process is morphing rotational sweep to simple extrusion, mapping from sweep angle to length of extrusion should be calculated to make actual custom-fit pillow design.

The overview of morphing process is shown on figure 5.17. Morphing is only considered on XZ plane. Y axis is not considered because Y value of arbitrary point on the model is always same regardless of morphing. However, as shown on figure 5.18 and figure 5.19, distortion occurs while morphing geometry from rotational sweep to simple extrusion. To minimize the distortion, neutral line position L_N is introduced to minimize the distortion which is shown on figure 5.17. In the process of morphing, the length of the neutral line is preserved. Because geometry where face contact occurs is very sensitive to human, selecting reasonable neutral line position should be suggested.

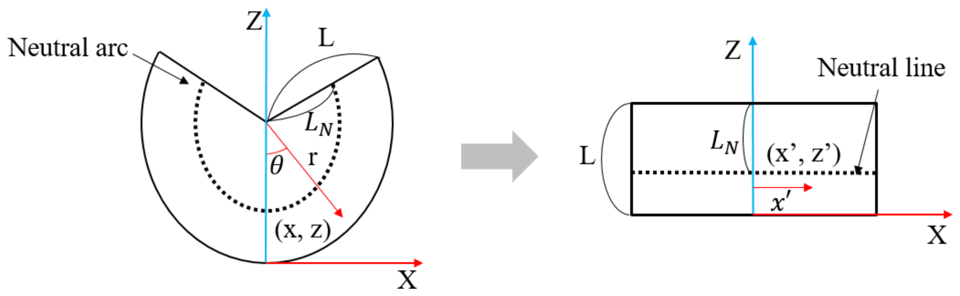


Figure 5.17 Overview of morphing process

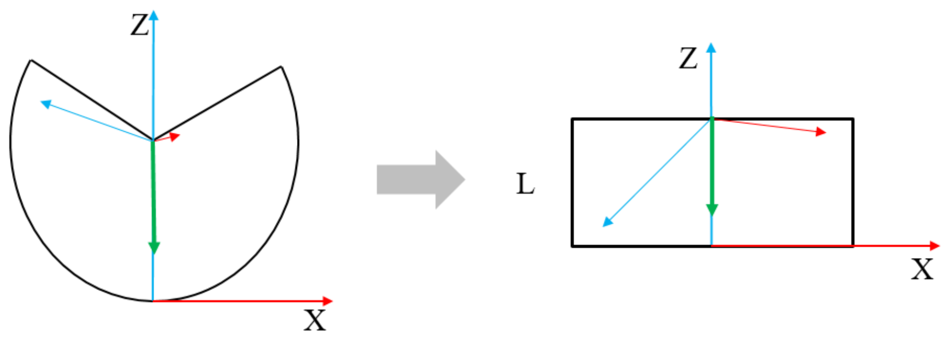


Figure 5.18 Distortion of vectors by morphing process

Figure 5.19 Distortion of area by morphing process

Before calculating the neutral arc position, morphing method should be explained. First, rotational sweep variables are expressed in terms of pillow design coordinate variables in equation 5-1 using symbols from figure 5.17.

$$\begin{cases} r = \sqrt{(L-z)^2 + x^2} \\ \theta = \tan^{-1}\left(\dfrac{x}{L-z}\right) \end{cases} \quad \textbf{(5-1)}$$

Based on the rotational sweep variables, Extrusion variables are expressed in terms of rotational sweep variables considering neutral line as shown in equation 5-2 using symbols from figure 5.17.

$$\begin{cases} x' = L_N\theta \\ z' = L - r \end{cases} \quad \textbf{(5-2)}$$

From geometric data expressed on XYZ frame such as figure 5.16, the geometric data is morphed into $X'Y'Z'$ frame with relationship from equation 5-1 and 5-2. while L is the height of tragion obtained from Chapter 4.3.2, neutral line position L_N is still not unknown, which should be calculated.

To select calculate the position of neutral arc, distortion analysis is conducted between rotational sweep and simple extrusion. The distortion can be defined as variation of area between two methods. Infinitesimal area of each variables is shown on equation 5-3 referencing figure 5.19.

$$dA = rdrd\theta$$

$$dA' = dx'dz' \quad \textbf{(5-3)}$$

Then, variance of area is calculated as shown on equation 5-4

$$\frac{dA'}{dA} = \frac{dx'dz'}{rdrd\theta} = -\frac{L_N}{r} \quad \textbf{(5-4)}$$

Distortion is small when the absolute value of the area variance is close to 1. This implies that distortion is small when point is near the neutral line. From the data analyzed by Cai [18], maximum radius of human is approximately 95mm and minimum radius is 55mm for ordinary men. To minimize distortion, radius of neutral arc is selected as harmonic mean of these two values which is approximately 70mm.

Obtained custom-fit pillow geometry with morphing applied is shown on figure 5.20. W lattice structure, the same lattice structure of third design, is applied to produce this pillow. Produced pillow is shown on figure 5.21. It took 86 hours to produce the pillow. Actual usage of subject is shown on figure 5.22. This time, subject was satisfactory with the designed custom-fit pillow.

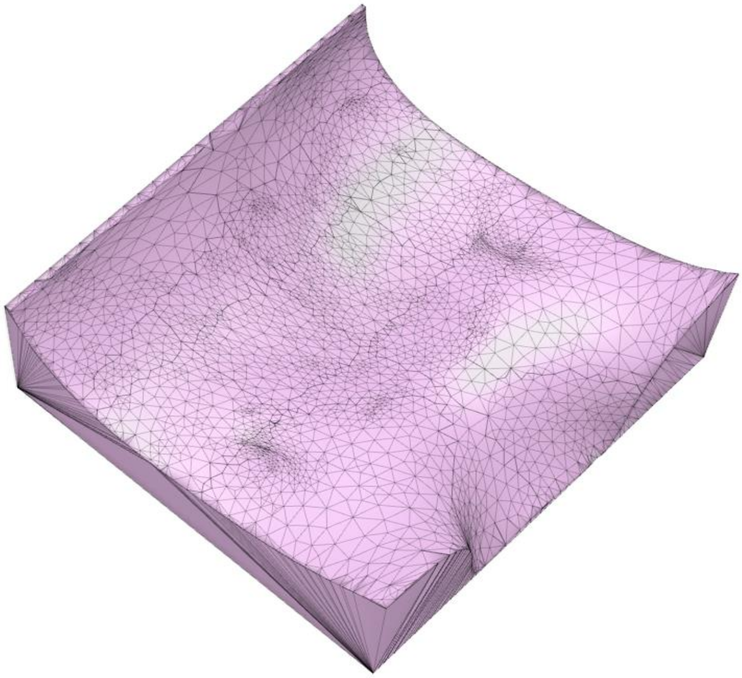


Figure 5.20 Obtained pillow geometry data with morphing applied

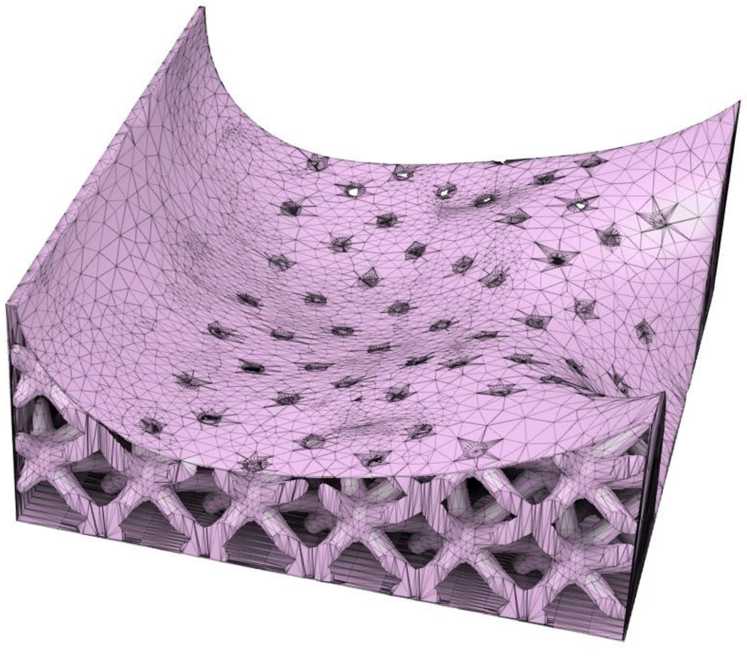


Figure 5.21 Perforation and infill structure applied to pillow geometry

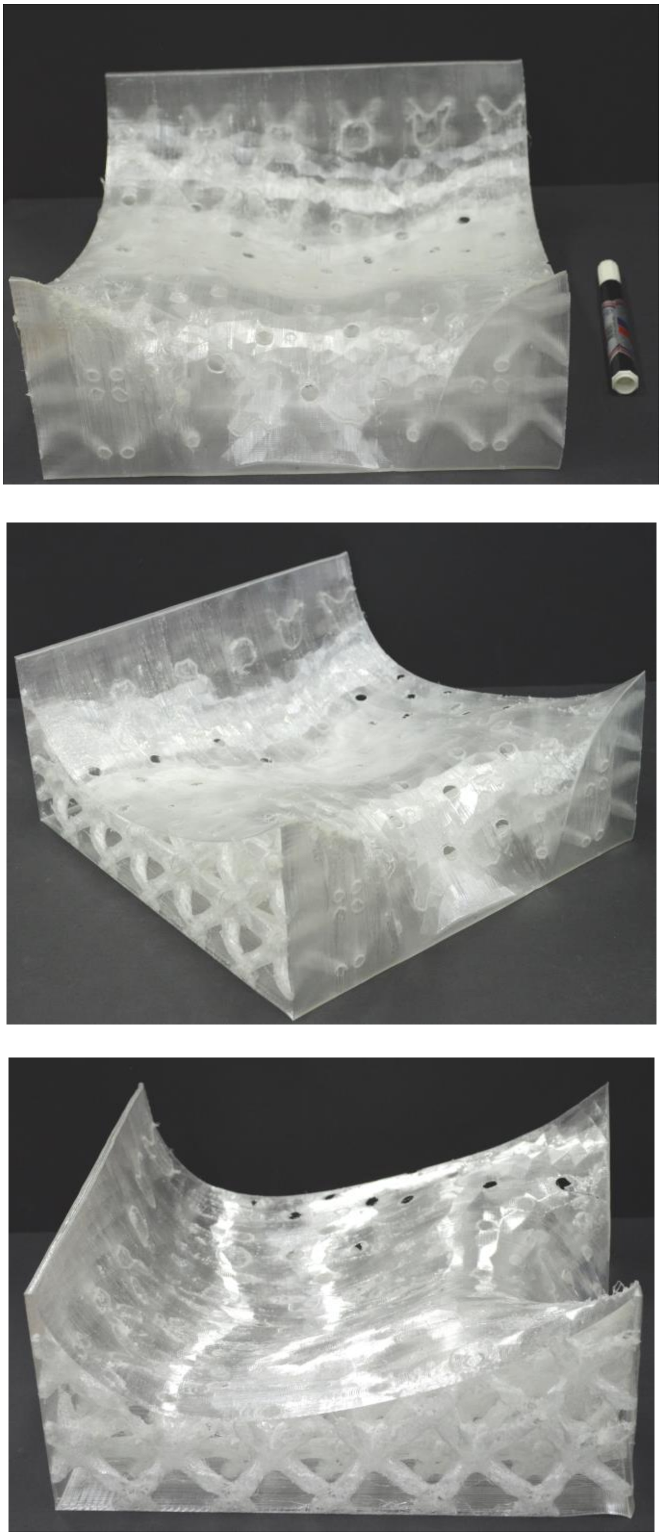
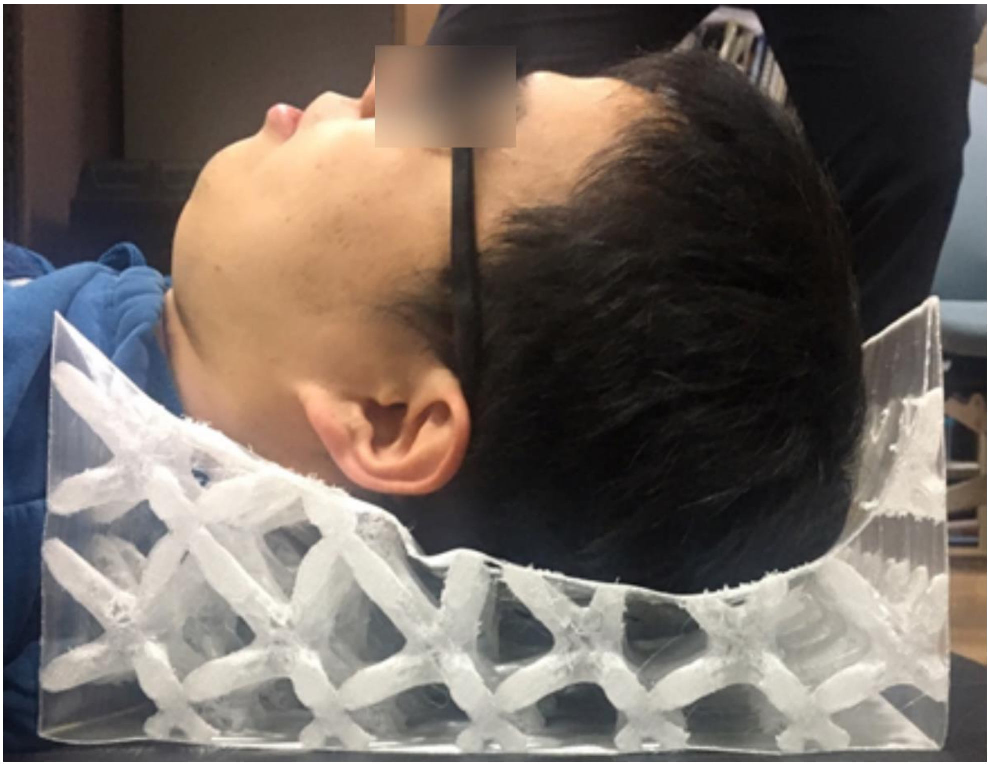


Figure 5.22 Produced pillow based on fourth design

(a)

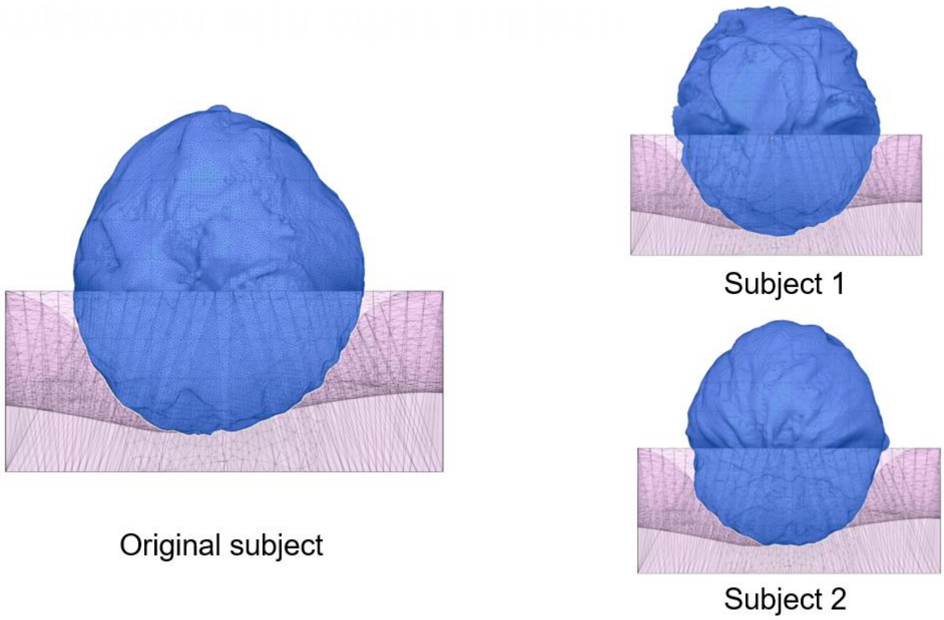


(b)

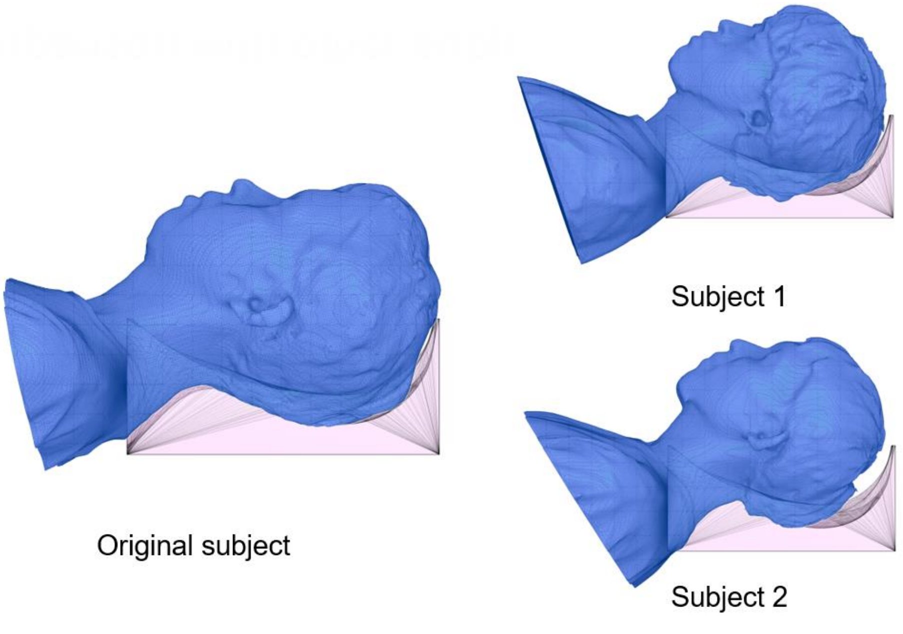
Figure 5.23 Actual usage of pillow of the subject (a) top view, (b) side view

5.5. Comparison with other subjects

Some head data were obtained from other subjects. Head data from other subjects were aligned by the same process suggested on Chapter 4. The result of alignment is shown on figure 5.24. The results show that a custom-fit pillow for an individual does not fit well to other subjects, validating the custom-fit pillow is unique for each individual.



(a)



(b)

Figure 5.24 Comparison with other subjects (a) front view, (b) side view

Chapter 6. Conclusion and discussion

Method to design custom-fit pillow regarding cervical spine maintenance was proposed in this research. The result of the produced pillow based on final design shows the uniqueness of the custom-fit pillow and the satisfaction of the participant.

The process of design and manufacturing custom-fit pillow contributed production of pillow with TPU material and design method of pillow based on the head data and previous pillow analyses.

Limitation of this research mainly lies on small number of participants and lack of analysis on the actual cervical spine stress. This could be improved by increasing the number of participants and performing finite element analysis of cervical spine stress as Ren's study have done [16]. Moreover, extraction of feature points should be more elaborated, due to ambiguity of actual location of shoulder tip point of cervical curvature angle. To improve the extraction of feature points, an automated process of feature point extraction based on anthropometric studies should be considered.

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초록

대량생산은 대중에게 많은 제품을 보다 저렴한 가격에 제공하였으며, 제품에 대한 수요를 만족시켜 인류에게 보다 나은 삶의 질을 이끌었다. 그러나 시간이 지남에 따라 소비자 개인의 특성에 맞춘 제품에 대한 요구가 생기기 시작했으며, 이는 제조기술의 발달로 맞춤형 제품의 생산단가가 저렴해져 이러한 욕구가 충족이 되기 시작했다. 특히 신발, 재킷, 바지 같은 제품들은 꾸준히 연구되어온 각 제품에 대한 정교한 분석들을 기반으로 여러 회사에서 고객을 위한 사용자 맞춤형 제품을 이전보다 저렴한 가격으로 제공하고 있다. 그러나 모든 제품이 맞춤형 제품으로 제작되는 것은 아니며, 몇몇 제품의 경우, 충분한 분석이 진행되었음에도 불구하고 사용자의 신체 데이터를 유용하여 사용자 맞춤형 제품의 설계 및 제작이 시도되지 않기도 했다.

본 연구에서는 기존에 행해졌던 베개의 연구들을 기반으로, 사용자 맞춤형 베개를 설계하고 제작하였다. 우선 사용자의 두상 데이터를 시중의 휴대용 스캐너를 이용하여 획득하였다. 이를 기반으로 베개를 설계함에 있어 경추에 걸리는 부담을 최소화 하기위하여 고려되는 경추의 만곡각도를 사용하여 베개를 설계 하였다. 총 네번의 설계시도가 행해졌으며, 첫번째 설계에서는 생산된 배게가 경추 자세 유지에 도움이 되는지 확인하였다. 두번째 설계에서는 생산 과정 중 고려되는 베개 모델의 내부 구조를 변경하여 베개의 강성을 조절하였으며, 세번째

설계에서는 옆으로 눕는 자세를 고려한 베개의 설계를 진행하였다. 마지막 설계에서는 이전 설계에서 문제로 제기된 반듯이 누운 자세와 옆으로 누운 자세를 변환하는 과정을 해결하였다. 최종적으로 설계된 베개가 사용자의 두상데이터에 맞게 설계되었음을 보였으며, 실제로 제작된 베개가 사용자에게 맞게 설계되었음을 보였다. 다른 사용자들이 사용하였을 경우에는 베개가 맞지 않음을 통하여 고유함을 증명하였다.