



## CUSTOMIZED HALLUX VALGUS SPLINT DESIGN FOR 3D PRINTER

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### ABSTRACT

In this study, a software was developed to create a splint model based on patient parameters in WPF (Windows Presentation Foundation) platform. By entering parameters to the software such as patient's foot size, hallux valgus grade, finger thickness and length, creation of a personally customized splint design is provided. A standard splint model, which was previously designed in the 3D program, is installed in the software. Later, according to the entered parameters of the patient, the splint is formed as customized for the individual. Thus, the patient's discomfort arising from the use of the splint disappears. Along with the continuous and regular use of splints, however, it appears that the healing process runs faster. A custom-designed splint and a splint produced by manual labor and mold making techniques were compared in terms of production technique, material, cost and duration. According to this comparison, a custom splint produced by 3D printer provides advantages in terms of cost and production time. However, it seems that it does not have any advantage in terms of material and production techniques used.

**Keywords:** 3D Printer, Splint, Hallux Valgus, 3D model, WPF.

## 3D YAZICI İÇİN KİŞİYE ÖZEL HALLUKS VALGUS ATELİ TASARIMI

### ÖZET

Bu çalışmada WPF (Windows Presentation Foundation) platformunda hasta parametrelerine karşılık atel modeli oluşturan bir yazılım geliştirilmiştir. Yazılıma hastanın ayak ölçüsü, halluks valgusun derecesi, parmağın kalınlığı ve uzunluğu gibi parametreler girilerek kişiye özgü atel tasarımının oluşturulması sağlanmaktadır. Yazılım içerisine daha önceden 3D programında tasarlanmış standart bir atelin modeli yüklenmektedir. Daha sonra da hastanın girilen parametrelerine göre atel, kişiye özgü biçimlendirilir. Böylece hastanın atel kullanımından dolayı oluşan rahatsızlığı ortadan kalkmaktadır. Bununla beraber sürekli ve düzenli atel kullanımının sağlanması ile iyileşme sürecine daha hızlı girildiği görülmektedir. Kişiyeye özel tasarlanan atel, el işçiliği ve kalıp döküm yöntemleri ile üretilmiş atelin üretim tekniği, malzeme, maliyet ve süre bakımında karşılaştırılması yapılmıştır. Bu karşılaştırma sonucuna göre 3D yazıcıdan kişiye özel üretilen atel maliyet ve üretim süresi yönünden avantaj sağlamaktadır. Fakat kullanılan malzeme ve üretim teknikleri yönünden herhangi bir avantajının olmadığı görülmektedir.

**Anahtar Kelimeler:** 3D Yazıcı, Atel, Halluks Valgus, 3D model.

## 1. INTRODUCTION

The 3D printer is a device that allows the pre-designed models to be created by additive manufacturing. 3D printers have introduced to the world of science in the 1970s [1]. The first 3D printer example was made by Chuck Hull in 1984 [2]. However, it has been widely used since 2010. Today, with 3D printers, products are commonly obtained using 3D model files with extensions of STL and OBJ [3]. With 3D printers, conventional cutting, drilling and shaving have ceased [4-5].

3D printers nowadays are used in every field that needs fast prototyping and molding [6]. Especially in the field of health, 3D printer is preferred in the production of medical products for therapeutic purposes. Many medical products are manufactured as standard, regardless of the age, gender, and grade of the disease at the patient [7]. As a result, the treatment process of the disease is adversely affected. This necessitates the customized production of medical products [8].

The big toe is the place that carries the most loads of body weight after the heel. Therefore, disorders affecting the big toe are very important. One of these disorders is Hallux Valgus, which is shown in Figure 1 [9]. Hallux valgus is a deformity that can easily be noticed by looking at the foot [10]. Hallux valgus, is the lateral deviation of the metatarsal of the toe, and the shift of proximal phalanx to medial. At the advanced stage of the disease, it causes subluxation in the joint [11].



**Figure 1.** Hallux valgus.

Internal causes in the etiology of hallux valgus deformity; anatomic changes in bone structure, abnormal lower extremity biomechanics, joint laxity, joint hypermobility and neuromuscular [12]. According to a study by Hardy and Clapham, 88% of Hallux Valgus condition is seen in women for [13]. To measure the level of hallux valgus, an angular measurement is made between the proximal phalanx of the toe and the metatarsus. This measurement is made using data obtained from X-ray [14]. In addition, anthropometric measurements are preferred in the detection of hallux valgus angle [15]. According to the measurement results, hallux valgus is diagnosed at angular changes that are over about 15 degrees since the slight deviation of the big toe is normal. According to Kelliklan; Light up to 20 degrees, up to 30 degrees, and up to 40 degrees are classified as advanced [16].

In hallux valgus, a minor angulation disables the abductor hallucis muscle, leaving only a soft joint capsule that pulls the big toe to the lateral. Conservative treatment is recommended before surgical treatment [12]. In order to avoid going to Hallux valgus surgery, the patient is asked to take physical therapy and preventive treatment. Therefore, the patient is given a night splint [13]. The study by Groiso found that there were many splint types on the market [14]. The splints are very difficult to adapt to different sizes and anatomical variations in mass production. Some splints in the market are elastic, leading to failure of treatment.

In this study, a software was developed to provide customized production by entering the parameters of the patient into the pre-designed splint model. The 3D splint design is developed in binary format with the open source library QuantumConcepts.Format.StereoLithography. Patient's hallux valgus grade,

XY value of the foot, thumb diameter and length data are entered in the software. The new splint design is rendered by recreating the reference points of the model according to the entered data. The customized reproduction of the splint is saved as stl. As a result of this work, it is aimed to provide a rigid pull to soft tissues with specially designed splint. With the continuous and regular use of the specially designed splint, it is seen that the patient enters in the healing process faster.

## 2. BACKGROUND

### 2.1. Windows Presentation Foundation (WPF)

WPF is a software technology introduced by Microsoft in 2003. Design and coding sections are independent from each other in the infrastructure of WPF technology. Vector based XAML is used instead of pixel based structure in the design area [17]. The WPF platform uses the Direct-X infrastructure. Therefore, graphics applications use the processor and memory of the graphics card instead of the central processor and RAM. However, increasing performance in graphical applications does not adversely affect the resource consumption [18].

### 2.2. Extensible Application Markup Language (XAML)

XAML is a markup language that provides the creation of static and dynamic user interfaces developed in the design part of WPF applications. While XAML is not a programming language, application logic and events are not in the codebehind files. The XAML element is actually an XML representation of the attributes that represent the NET CLR class. Therefore, the properties of any object can be easily changed. Property concepts and events known from form applications are called attributes in XAML [19].

### 2.3. STereoLithography (STL)

STL is a format in which the outer surfaces of 3D objects are composed of a mathematical structure and a large number of triangular surface lists [20]. STL files have two different formats, Binary and ASCII, depending on the purpose of use and structure. As shown in Figure 2, the syntax of Binary and ASCII STL files are different. ASCII STL files take up more space than the Binary STL files [21].

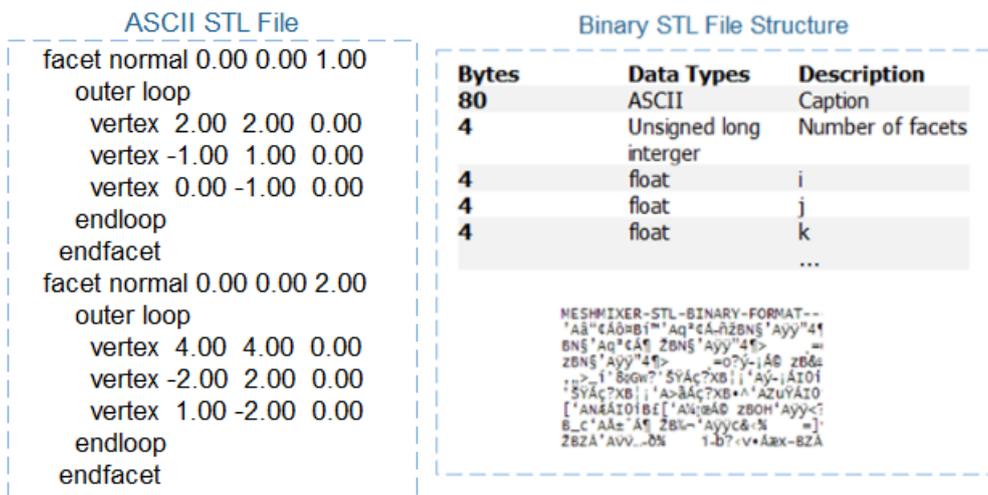


Figure 2. ASCII and binary STL file.

## 2.4. Geometric Code (G-code)

G-code is a command line showing the route, the speed, the ratio of the material extruded from the extruder, the plate temperature and the path to be followed in the 3-axis coordinate plane. In order to print objects on 3D printers, it is necessary to initially create gcode commands. G-code files for 3D objects are created with slicing tools [22].

3D printers perform G-code commands in sequence, starting from the first line. The G-code consists of 3 parts as shown in figure 3. The first part is to prepare the printer for pre-printing start. The second part contains the route the printer will follow for printing. The third part is to reset the printer after printing to wait for the next production [23].

|  |  |
|--|--|
| <b>G28</b> (return to initial point for nozzle)        | <b>G1 F900 X125.630 Y90.370 E2.23770</b> |
| <b>M107</b> (turn off fan)                             | <b>G1 X125.630 Y109.630 E3.07847</b>     |
| <b>M104 T0 S0</b> (extruder cooling)                   | <b>G1 X74.370 Y109.630 E5.31618</b>      |
| <b>M140 S0</b> (Bed Surface cooling)                   | <b>G1 X74.370 Y90.370 E6.15695</b>       |
| <b>M84</b> (engines stop)                              | <b>G0 F6000 X74.790 Y90.790</b>          |
| a)   | <b>G1 F900 X125.210 Y90.790 E8.35798</b> |
| <b>G90</b> (set origin point)                          | <b>G1 X125.210 Y109.210 E9.16209</b>     |
| <b>M82</b> (prepare the extruder)                      | <b>G1 X74.790 Y109.210 E11.36312</b>     |
| <b>M106 S0</b> (wait in fan open position)             | <b>G1 X74.790 Y90.790 E12.16722</b>      |
| <b>M140 S100</b> (heating bed surface heating to 100c) | <b>G1 F1800 E11.16722</b>                |
| <b>M190 S100</b> (waiting until temperature to 100c )  | <b>G0 F6000 X80.630 Y96.630</b>          |
| c)   | b)                                       |

**Figure 3.** Structure of G-code a) startup section b) development section c) completion section.

## 3. DESIGNING OF HALLUX VALGUS SPLINT

The study was developed using WPF technology in Visual Studio 2017. The open source QuantumConcepts.Format.StereoLithography library is used for reading, editing and rebuilding Binary STL files in WPF. A new STL file is created by taking the patient's hallux valgus grade, foot XY lengths, the length and diameter of the big toe to create a patient specific splint design. With the STL file created, the gcode script is created using the slicing tool.

### 3.1. Decide of Hallux Valgus Angle

As shown in Figure 4, the angle between the axis passing through the middle of the tip of the big toe and the axis passing through the metatarsal bone determines the curve of the splint. If this angle exceeds 15 degrees, we can talk about the existence of hallux valgus for the patient. In the first 15 degrees, the splint is being used for preventive purposes.

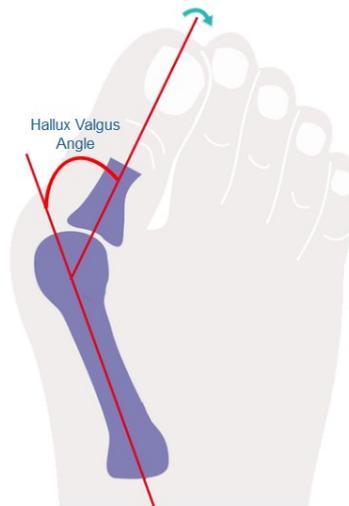
#### Remarks

- In the case of a patient between 0-20 degrees, this angle should be adjusted to 0 degrees without giving any curve.
- If it is between 21-31 degrees, the angle should be reduced to 5-15 degrees.
- If it is between 32-41 degrees, the angle should be reduced to 16-25 degrees.
- If there is a higher angle, surgery should be recommended.

The 2-level hallux valgus grade, which ranges from 21 to 40, is calculated according to Equation 1.

$$C_x = C_y - 16 \tag{1}$$

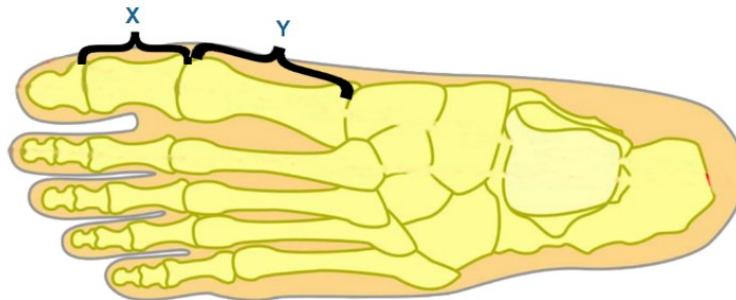
$C_y$ : Input angle  $C_x$ : Splint angle



**Figure 4.** Hallux valgus angle.

### 3.2. Measurement of Foot XY

In order for the patient to be able to use the splint comfortably, the foot size should be taken and processed into the system. This measure is represented by  $X$ , the distance between the distal tip and the proximal tip of the thumb proximal phalanx bone, as shown in figure 5. The distance between the cuneiform medial and the *metatarsal* bone distal is represented by  $Y$ .



**Figure 5.** XY length.

### 3.3. Big toe diameter and the length measurement

The splint should be fixed to the big toe to keep it stable on the patient's foot. Therefore, in the splint design, the diameter and length of the big toe are entered in cm. This measurement allows the patient's foot to move faster to the anatomical position.

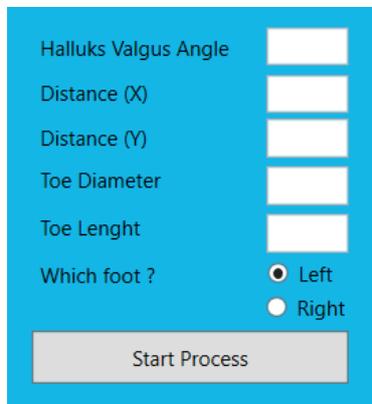
### 3.4. Software Development

The software that generates the custom splint design was developed using the C# 6.0 programming language with WPF. Helix3DViewer control is used to show the 3D splint model in software and 3 axis control [24]. The 3D standard splint model is designed in Binary STL format with 3D program for left and right foot. The designed reference model is loaded in the software during the opening. The Helix3DViewer displays and reads the references in the model while the model is loading. The coding required for the reference points to be read from the model and loaded into the generic sequence named facets is shown in Figure 6.

```
private const int DefaultBufferSize = 1024;
public string Name { get; set; }
public IList<Facet> Facets { get; set; }
public STLDocument()
{
    this.Facets = new List<Facet>();
}
public STLDocument(string name, IEnumerable<Facet> facets): this()
{
    this.Name = name;
    this.Facets = facets.ToList();
}
```

**Figure 6.** Reading of facets from STL file.

The parameter entry screen shown in Figure 7 is defined by the specialist for patient data entry. The measured values are compared with the reference values after their input to the system. If there is a change in the reference values, the new value is added to the model. The specially designed new model is transferred to the existing STL file as shown in Figure 8.



**Figure 7.** Parameter entry screen.

```
public void WriteBinary(Stream stream)
{
    using (BinaryWriter writer = new BinaryWriter(stream, Encoding.ASCII, true))
    {
        byte[] header = Encoding.ASCII.GetBytes("Binary STL generated by AAS");
        byte[] headerFull = new byte[80];
        Buffer.BlockCopy(header, 0, headerFull, 0, Math.Min(header.Length, headerFull.Length));
        writer.Write(headerFull);
        writer.Write((UInt32)this.Facets.Count);
        this.Facets.ForEach(o => o.Write(writer));
    }
}
```

**Figure 8.** Writing of new facets to STL file.

Before saving the splint model created with new reference points, it is shown in Helix3DViewer control as seen in Figure 9. To carry out the production of the previewed splint via 3D printer, the gcode script needs to be created. Production of the splint is carried out from any 3D printer with the command file belongs to the splint.

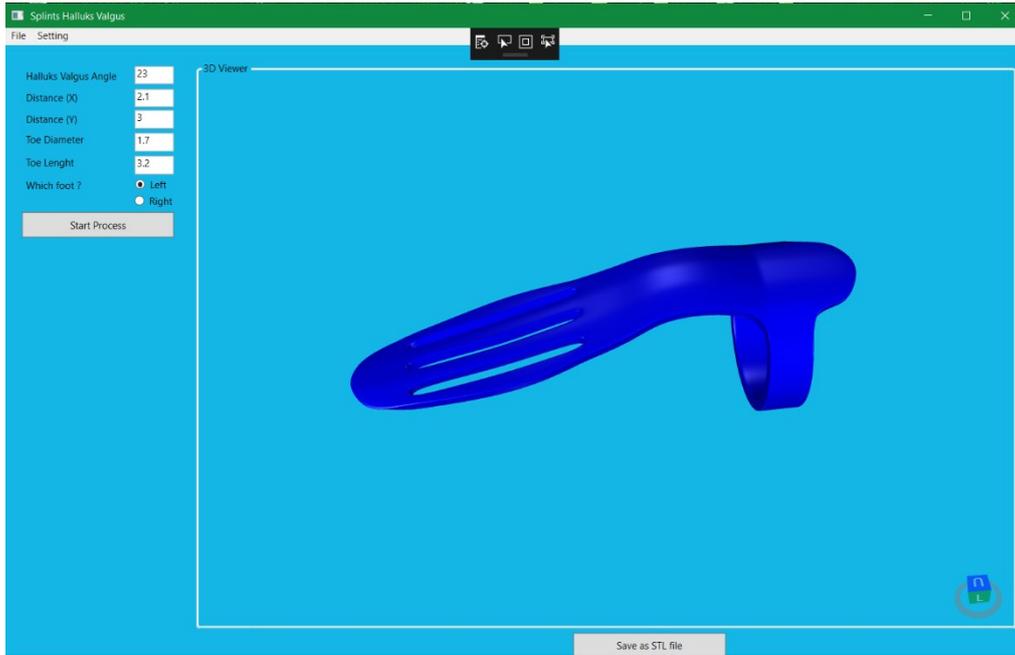


Figure 9. Model preview.

### 3.5. To carry out the production of splint via 3D Printer

The splint has been designed for 3 different individuals in accordance with the patient's foot measurements and level of hallux valgus disease. The measurements used in the study were obtained from 2 adults and 1 child. The STL file produced for the designed splint models was prepared for printing with the CURA slicing tool. The PLA (Polylactic Acid Thermoplastic Polyester) filament consumption values required for printing 3 different custom-designed splints on the 3D printer are given in Table 1. The printer settings used to print the models on the 3D printer are given Table 2.

Table 1. Consumption and production times of splints.

| Design Scales of Splint   | Material Consumption (PLA) | Elapsed Time |
|---|----------------------------|--------------|
| Angle : 35<br>X: 4 cm<br>Y: 3.5 cm<br>Diameter: 1.82 cm<br>Length: 4 cm     | 5 gr (1.50 meter)          | 21 min.      |
| Angle : 24<br>X: 4.2 cm<br>Y: 3.7 cm<br>Diameter: 2.1 cm<br>Length: 3.8 cm  | 5 gr (1.55 meter)          | 22 min.      |
| Angle : 18<br>X: 2.1 cm<br>Y: 2.9 cm<br>Diameter: 0.99 cm<br>Length: 2.9 cm | 3 gr (1.04 meter)          | 15 min.      |

Table 2. 3D Printer Properties.

|                    |      |
|--------------------|------|
| Diameter (mm)      | 1.75 |
| Flow (%)           | 100  |
| Nozzle Size (mm)   | 0.4  |
| Fill Density (%)   | 100  |
| Print Speed (mm/s) | 50   |

#### 4. RESULT

The comparison of other techniques for the custom splint that is designed with WPF in terms of production technique, material, time and price information is given in Table 2. The study conducted according to these results revealed that it was produced with lower cost and in a shorter time than the standard splint. It is envisaged that it will be preferred more in terms of usage thanks to this advantage, as well as production with custom measurements.

The splints used for Hallux valgus disease are administered as a night treatment for the patient. The endurance characteristics of the materials are not used in the comparison since the body weight will not be carried by the splint during the treatment.

**Table 2.** Comparison of manufacturing methods of splints.

| Method       | Material      | Time avg. | Consumption avg. | Fee avg.           |
|--------------|---------------|-----------|------------------|--------------------|
| Manual Labor | Thermoplastic | 60 min    | 250 gr           | 5.0 Turkish Liras  |
| Mold Making  | Polypropylene | 90 min    | 300 gr           | 3.0 Turkish Liras  |
| 3D Printer   | PLA or ABS    | 19 min    | 5 gr             | 0.50 Turkish Liras |

#### 5. CONCLUSION

Nowadays, 3D printers are used in production processes with rapid prototyping. Especially in the field of health, it is seen that patient-specific production has a positive effect on the treatment process.

Night-time splint is used for the treatment of hallux valgus disease that does not require surgical operation. These splints are produced in a standard size. Uneasiness is observed due to the patient's use of the splints because of the difference in disease grade and foot structure. Therefore, the healing process of the disease is prolonged or the degree of the disease is increasing.

By entering parameters to the software such as patient's foot size, hallux valgus grade, finger thickness and length, creation of a personally customized splint design is provided in the study. Along with the continuous and regular use of splints that was designed specifically considering the current situation of the patient and the grade of the disease, however, it appears that the healing process runs faster.

A custom-designed splint and a splint in standard dimensions by production techniques were compared in terms of production technique, material, cost and duration. According to this evaluation, a custom splint produced for 3D printer provides advantages in terms of cost and production time. However, it seems that it does not have any advantage or disadvantage in terms of material and production techniques used.

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