Reverse innovative design and manufacturing strategy for optimizing production time of customized orthotic insoles with CNC milling

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Abstract. Reverse innovative design (RID) of insole shoe orthotics for patients with diabetes and the manufacturing strategy in optimizing the production time of the insole were examined in the present work. The plantar surface of the feet from two female patients was scanned using a 3D scanner yielding a 3D mesh foot for each patient resulting in an STL file format. The geometric shapes of the 3D models of the feet were fitted very well using curve based surface modeling (CBS-modeling) for insole orthotics design and integrated with CAM (computer-aided manufacturing). Optimization of the manufacturing time was simulated in CNC milling with the Taguchi approach. The manufacture of the optimal insole design was achieved at the optimum machining parameters such as toolpath strategy (A) with raster machining, spindle speed (B) of 15000 rpm, feed rate (C) of 900 mm/minutes, and step over (D) about 0.30 mm. The optimal design of the orthotic insole has the geometric tolerance (D) of 0.75 mm for patient 1 and 1.50 mm for patient 2. The optimal machining time for the insole of patient 1 is 3.79 and 4.02 hours for patient 2. The optimal machining time for the insole of patient 1 is 227.48 minutes and 241.65 minutes for patient 2. These valuable data are needed for the real manufacturing process of insole material in CNC milling.

1. Introduction

Three-dimensional (3D) scanning, computer aided design (CAD), and computer-aided manufacturing (CAM) have played a significant role in manufacturing foot molds and custom foot orthotics components [1-3]. The availability of CAM software for facilitating CNC machines in the manufacture of ankle foot orthotics (AFO) yielded a product with excellent dimensional accuracy, good manufacturing precision, and performance similar to handcrafted AFO’s [3]. Additionally, recent studies demonstrated the manufacture of orthosis by a CNC machine yielded a product with positive subjective comfort ratings and similar to the biomechanical gait parameters of orthoses fabricated using traditional methods [4]. Correspondingly, 3D scanning tools, CAD, and CNC machines are the most compact tools available on the market for many design professionals because these systems are easily approachable and affordable, as well as having a tremendous clinical applicability in the designing of insole shoe
 orthotics [5].

Further, the use of CAD in the shoe and sandal industry is necessary because it can shorten the presentation time of a novel product for consumers and reduce the product development costs [5]. Currently, many CAD tools are available such as Inventor, Solidworks, Power SHAPE, Art CAM, Toolmaker, Copy CAD, the PS Mold Maker, and Ortho model, which can assist design engineers in quickly bringing the concept about with realistic precision and consistent with the 3D CAD models [6]. Additionally, the availability of CAD software can help for various 3D models leading to shifting product development from the physical model to digital ones or from the 2D drawing process design of the 2.5D / 3D image model [1, 6]. Here 3D modeling has become an important part of the digital development process that may include design, modeling, and simulation [1]. If a digital form of a similar product for a new design is available in the database, searching techniques can be used to find product models with similar and fixed designs [1, 9, 12-14]. In this way, a novel design can be improved by reuse, in whole or in part, from a previous design.

As a response to the rapid progress in the 3D data acquisition, reverse engineering (RE) has gained widespread acceptance in the design community. During this time, RE can be used for designing or modifying a product from an existing product. Now RE plays an important role within the company for engineering design. A number of studies on the RE product design of shoe insole orthotics have been also reported [3, 5, 6]. Here, the output of 3D scanning of a foot model in the form of a 3D mesh or point cloud can be directly processed on 3D printers or CNC machines [14, 15]. However, most of the previous studies have only focused on the development of RID (Reverse Innovative Design) for the insole shoe orthotics without performing an optimized design approach. After the 3D scanning process of obtaining foot images and converting them into the digital form data, the designed model can be directly fabricated by additive manufacturing through (3D) printing or a CNC machine [5, 8, 9, 13]. The utilization of a CNC machine for manufacturing CAD shoe insoles based on models of the normal human foot is very common, but this manufacturing process was done without the levels of design optimization in CAE as required in the method of RID [1, 12, 13] that was shown in Figure 1.

The main objective of present research is to investigate the RID application for designing custom insole shoe orthotics for patients with diabetes. In this way, characteristics of the patient's foot surface are obtained at once from the 3D data scan, while Geomagic Studio X is used to digitize the geometric pattern in 3D CAD systems.

2. Material and Method

2.1. Use of 3D scanner for measurement of the foot

In the present study, the feet of two female patients between 50-75 years old and weight between 55-70 kg were scanned for the 3D model of insole shoe orthotics design. Both patients’ feet have characteristics of a bone protruding near the second toe of their feet (swollen bone). Figure 1 presents the workflow for designing the 3D model of the insole shoe orthotics. The 3D data acquisition process started by a 3D scan of the foot using a non-contact HandySCAN scanner 700™ that is insensitive to vibration and unable to stick to the object. The 3D scanner is equipped with a white light laser to make data processing faster in the range from 5-10 minutes and to produce accuracy levels of about 5 μm.

The HandySCAN 700™ is equipped with seven intersecting laser beams to speed up shooting with a high precision of about 0.030 mm (0.0012 in). The process of 3D scanning the foot surface in both patients was done by attaching small black stickers as sensors on some parts of the surface contour of the foot.
2.2. Processing the STL file into a 3D mesh foot

3D CAD data of the foot were initially verified by color mapping with Geomagic Studio X software before they could be processed further. This verification enabled the size difference to be distributed in the input data of the 3D mesh and results of the RE are as represented with the corresponding color symbol. In this way, the color mapping was performed by comparing the 3D CAD surface and the 3D mesh STL with the same orientation. Comparative analysis of the characteristics of Geomagic Studio X and PowerSHAPE 2016 was performed in the present study. This color mapping took the sample points on the two images, which were compared and calculated for the gap between the dots, and subsequently displayed in shades of red to blue. For this purpose, the software of Geomagic Studio X was used to capture the output of the 3D scanner in digital form, which was displayed on the computer screen. Geomagic Studio X got data directly from a file that had been already scanned, while 3D scanning checked whether the processing of the network to get a 3D solid model mounted on the foot.

2.3. Base curved modeling of 3D CAD insoles

PowerShape 2016 software developed the 3D model of insole orthotics through several stages. The first stage included an application of CBS modeling for the initial 3D digital data that had been verified in the previous phase (Table 1). The CBS modeling reconstructed the 3D model of the insole shoe orthotics with an accurate result. This approach has been successfully applied for designing insole shoe orthotics for feet both without and with deformities [9, 12-14]. Accordingly, CBS modeling yielded a well-formed 3D surface using the created curves.

Furthermore, the solid 3D model of insole shoe orthotics could be obtained with a shaped fit to the original form of the foot surface. In this way, the software of PowerShape 2016 created design variations by changing the definition parameters of the product. In this way, the original 3D CAD models were enhanced by insole design parameters in the direction of axis X-Y (2D). This magnification provided a wide tolerance of 0.0, 0.75, and 1.50 dmm. The results of the design variables are considered as one of the factors to determine the optimal new designs.
2.4. The manufacture of insole shoe orthotics with a simulation in CAM

The optimal design of the new 3D model of insole shoe orthotics, at this stage, was obtained by performing a simulation-based Taguchi optimization in CAM [12, 13, 14]. Prior to the simulation, the selection of the cutting condition parameters is essential with respect to machining time. This condition is valuable data for determining the real process of manufacturing the insole with various materials. Five factors were selected as follows: machining toolpath strategy, spindle speed, feed rate, step over, and typical insole product based on the width of the tolerance. The first of the four factors is related directly to the process of machining in CAM and CNC machines. Instead, a factor of typical insole products was included in the orthogonal array (OA) to get the new design of the optimal model. Each factor was assigned three levels. The response was measured as the machining time in the CAM PowerMILL 2016 simulation of each treatment. Orthogonal array in this research is defined as L2734. There are 27 treatment-appropriate factor levels in OA and are set out to get a response of machining time (Table 2). The machining time was calculated when the cutter milling began in the simulation until the toolpath strategy simulation ended. The process was shown in Figure 2.

![Figure 2](image)

Figure 2. workflow for optimizing simulation process manufacturing of the insole shoe orthotics using CAM

3. Results

3.1. 3D scanning/digitizing of each foot and 3D CAD model of insoles

The shape of the foot for both patients and the results of the output scanning in the STL file and verification results by Geomagic Studio X are given in Figure 3. In this way, the 3D CAD model of the insole with CBS modeling was obtained, while stages of developing 3D CAD insole models from the fixed solid model of each patient’s foot are presented in detail in Figure 4. The original 3D CAD model of the insoles that fit the foot surface contours of both patients is presented in Figure 8a. Moreover, the design variations of the insoles by changing the product definition parameters are displayed in Figures 5 b, c. Conversely, the simulation results of the insole shoe orthotics with PowerMILL 2016 on roughing and the finishing processes are given in Figure 2. The manufacturing simulation results of the 3D CAD model in CAM are shown in Figure 6 and the results for each machining time are presented in Table 3. These results were then examined using S/N ratio and ANOVA analysis to determine the significant factors that contributed to the optimum machining time.
Figure 3. Three Dimensional (3D) Foot model of diabetic patients: (a) physical model of the patient’s foot; (b) the output of 3D scanning in term of the STL file format; (c) output verification of 3D solid model of Geomagic Studio X and PowerSHAPE 2016

Figure 4. CBS-modeling iso_product DM involved in PowerSHAPE 2016 (a) Mesh importing & pre processes; (b) Rewiring; (c) Repoint, built and verification 3d surface to solid foot with solid doctor; (d) 3D solid model foot from mesh; (e) Oblique processing; (f) Foot wireframe; (g) Wire support; (h) Repoint wireframe curve; (i) Wire reconstruction; (j) Surface generating; (k) Surface curve editing; (l) 3D solid iso_diabetes [12-14]

Figure 5. The RID output for the insole shoe orthotics: (a) the two CBS modeling of pairs of the original 3D CAD models and real produk ISO_diabets; (b) the design variations by changing the product parameters of patient 1; (c) the design variations by changing the product parameters of patient 2
3.2. Effect of machining parameters on machining time of the insoles
In the present study, the term ‘signal’ represents the desired value (mean) for the response characteristic and the term ‘noise’ relates to the undesirable value (S.D) for the response. Thus, the S/N ratio represents the ratio of the mean to the S.D. In the Taguchi method, the S/N ratio is indicated for the quality of characteristics deviating from the desired value. The performance characteristic for the machining time (Tm) has been taken. Tables 1 and 5 present the results of the ANOVA analysis and the S/N ratio for Tm using the input data from the design of experiments for patients 1 and 2 (Table 1 and table 2).

| Table 1. Parameter Control machining |
|--------------------------------------|
| Factor | Level |
| A: toolpath strategy | raster 45, raster 90, step & shallow |
| B: spindle speed (rpm) | 13500, 14000, 15000 |
| C: feed rate (mm/min) | 850, 900, 950 |
| D: step over (mm) | 0.1, 0.20, 0.30 |
| E: tolerance | 0.5, 0.75, 1.50 |

| Table 2 Experimental design, the measured results and their calculated S/N ratios |
| No | Code | A | B | C | D | E | tool path | Spindle speed (rpm) | Feed rate (mm/rot) | type of insoles (mm) | Machining Time Simulation of patient 1 (minutes) | Machining Time Simulation of patient 2 (Minutes) |
|----|------|---|---|---|---|---|----------|-----------------|-----------------|------------------|----------------------|------------------------|
| 1  | 1    | 1 | 1 | 1 | 1 | 1 | Raster   | 14000          | 800             | 0.20             | 320.24                | 322.40                  |
| 2  | 1    | 1 | 1 | 1 | 2 | 2 | Raster   | 14000          | 800             | 0.75             | 318.40                | 320.40                  |
| 3  | 1    | 1 | 1 | 1 | 3 | 3 | Raster   | 14000          | 800             | 1.50             | 316.83                | 329.83                  |
|    |      |   |   |   |   |   |          |                 |                 |                  | 331.83                | 334.83                  |
| 25 | 3    | 3 | 2 | 1 | 1 | 1 | Step & Shallow | 15000        | 850             | 0.20             | 325.22                | 328.22                  |
| 26 | 3    | 3 | 2 | 1 | 2 | 2 | Step & Shallow | 15000        | 850             | 0.75             | 380.03                | 382.03                  |
| 27 | 3    | 3 | 2 | 1 | 3 | 3 | Step & Shallow | 15000        | 850             | 1.50             | 321.70                | 322.70                  |

| Table 3(a). Results of the ANOVA for Sq and % Rho for patient 1 |
|---------------|---------|-------|-----|---------|---------|---------|
| SOURCE | Sq | v | MQ | F_ratio | Sq ' | Rho% |
| A | 10.662,407 | 1 | 10662.4 | 4,2926 | 10.658,114 | 25.251 |
| B | 65.764,00 | 1 | 657,641 | 0.02648 | 65,737,590 | 0.156 |
| C | 1.957,445 | 1 | 1957.450 | 0.78806 | 1.956,657 | 4,636 |
| D | 27.525,715 | 1 | 27525.7 | 11.08170 | 27.514,634 | 65,186 |
| E | 2.014,864 | 1 | 2014.86 | 0.81117 | 2.014,053 | 4,772 |
| e | 0.000 | 5 | 0 | 0 | 0 | 0 |
| St | 42.226 | 17 | 2483.89 | 0,0000127 | 42.209,196 | 100 |
| mean | 2,483,894 | 27 | 2483.89 | 0,0000127 | 42.209,196 | 100 |
| ST | 0 | 27 | 42,209,196 | 0,0000127 | 100 |
The results of the optimum cutting parameters are much valuable for designing of factor \( f \) factors of were obtained. In contrast, the optimum cutting parameters for the second patient corresponded to step over control factor \( D \) at \( \text{level 3} \). ANOVA analyses for the machining time \( Tm \), spindle speed \( B \), feed rate \( C \), step over \( D \), and number flute tolerance \( E \) on \( Ra \) value for patient 1 and 2. Table 3.a. shown the \( F \)-ratio and the Rho\% that indicate the significance level. The \( F\text{-value} \) (11.08) and Rho\% (65.186\%) for factor D is the most prominent, which indicates that feed rate \( D \) was significantly contributed on the optimum value of surface roughness. The second significant factor is toolpath strategy \( A \) (25.25\%), followed by spindle speed \( E \) (4.77\%), feed rate \( C \) (4.64\%) and cutting speed \( B \) (0.156\%). Table 3.b. shown the \( F \)-ratio and the Rho\% that indicate the significance level. The \( F\text{-value} \) (3.67) and Rho\% (21.57\%) for factor \( D \) is the most prominent, which indicates that feed rate \( D \) was significantly contributed on the optimum value of surface roughness. The second significant factor is toolpath strategy \( A \) (20.21\%), followed by cutting speed \( C \) (19.44\%), tolerance \( E \) (19.47\%), and cutting speed \( B \) (19.3\%).

### Table 3(b). Results of the ANOVA for Sq and % Rho for patient 2

| Source | \( S_q \) | \( v \) | \( MQ \) | \( F_{\text{ratio}} \) | \( SQ' \) | Rho\% |
|--------|---------|-------|--------|----------------|--------|------|
| A      | 240654.5406 | 1     | 240654.5 | 3.435372 | 240651.1053 | 20.208 |
| B      | 229873.4108 | 1     | 229873.4 | 3.281471 | 229870.1293 | 19.303 |
| C      | 231551.0404 | 1     | 231551   | 3.305419 | 231547.735  | 19.444 |
| D      | 256904.7324 | 1     | 256904.7 | 3.667346 | 256901.0651 | 21.573 |
| E      | 231899.4217 | 1     | 231899.4 | 3.310392 | 231896.1113 | 19.473 |
| e      | 0        | 5     | 0       | 0            | 0       | 0    |
| St     | 1190883.146| 17    | 70051.95 | 0.0000127 | 0       | 0    |
| mean   | 70051.94976| 27    | 0       | 0            | 0       | 0    |
| ST     | 0        | 27    | 1190866.146| 100     | 100     | 100  |

Moreover, Table 3 presents the experimental results corresponding to the S/N ratio and the effect of each machining parameter on \( Tm \) at different levels. The \( F\)-ratio and % Rho (% contribution) for step over have the highest values in the table, which indicates that during machining of the insole for both patients (1 and 2), step over is more of a significant factor towards machining time than spindle speed and feeding rate. Based on table 3 In this paper, the ANOVA and effect of column were used to investigate the effects of the setting parameter such as toolpath strategy \( A \), cutting speed \( B \), feed rate \( C \), step over \( D \), and number flute tolerance \( E \) on \( Ra \) value for patient 1 and 2. Table 3.a. shown the \( F \)-ratio and the Rho\% that indicate the significance level. The \( F\text{-value} \) (11.08) and Rho\% (65.186\%) for factor D is the most prominent, which indicates that feed rate \( D \) was significantly contributed on the optimum value of surface roughness. The second significant factor is toolpath strategy \( A \) (25.25\%), followed by spindle speed \( E \) (4.77\%), feed rate \( C \) (4.64\%) and cutting speed \( B \) (0.156\%). Table 3.b. shown the \( F \)-ratio and the Rho\% that indicate the significance level. The \( F\text{-value} \) (3.67) and Rho\% (21.57\%) for factor D is the most prominent, which indicates that feed rate \( D \) was significantly contributed on the optimum value of surface roughness. The second significant factor is toolpath strategy \( A \) (20.21\%), followed by cutting speed \( C \) (19.44\%), tolerance \( E \) (19.47\%), and cutting speed \( B \) (19.3\%).

### 3.3. Optimized machining parameters for the low machining time of the insole

In this study, ANOVA and column effects were used to analyze the effects of toolpath strategy, spindle speed, feed rate, step over, and type of insole shoe orthotics on machining time simulations. Column effects of the Taguchi method as a simplified ANOVA have subjectively identified columns that may influence the response time [11]. The experimental designs were evaluated at a confidence level of 95\% (the level of significance is 5\%). ANOVA analyses for the machining time \( Tm \) confirmed that the most effective variable in the \( Tm \) value is the step over. The other variables influencing the \( Tm \) response are toolpath strategy, spindle speed, feed rate, and typical insole product. Therefore, step over (factor D) is the most significant factor affecting \( Tm \) value at the reliability level of 95\%.

In the milling operations, the machining time is mainly controlled by the cutting parameters. The S/N ratio analyses of the first patient recommended the optimum machining parameters for minimal \( Tm \) corresponding to the combination factors of \( A_1B_2C_3D_3E_2 \), in which raster machining of toolpath strategy \( A \) at level 1, spindle speed \( B \) at level 3 (15000 rpm), feeding factor \( C \) at level 3 (900 mm/rot), the step over control factor \( D \) with best results at level 3 (0.3 mm), and type of insole factor \( E \) at level 2 were obtained. In contrast, the optimum cutting parameters for the second patient corresponded to the factors of \( A_1B_2C_3D_3E_1 \) in which the toolpath strategy \( A \) of raster machining at level 1, the spindle speed of factor \( B \) at level 3 (15000 rpm), the feeding factor \( C \) at level 3 (900 mm/rot), the step over control of factor \( D \) at level 3 (0.3 mm), and typical insole of factor \( E \) at level of 3 could be determined. The results of the optimum cutting parameters are much valuable for designing a machining approach for the insole in real CNC machines. The results of this research have been proven by making an orthotic ankle foot and used by both diabetic patients with good results [9, 13, 14, 15].
4. Conclusions
RID was successfully applied in the design of a 3D foot mesh on the original solid models of both patients, as well as a features-based 3D CAD model with parameter CBS modeling. The design varied by changing the product definition of the parameter and a new design of insole shoe orthotics can be optimized by a CAM simulation. Manufacturing simulations provided that the optimal cutting parameters for patient 1 were raster machining strategy at the toolpath spindle speed of 15000 rpm, the feed rate of 900 mm/minutes, step over of 0.3 mm, and the typical insole product with a wide tolerance 0.75 mm. For patient 2, raster machining strategy at the toolpath spindle speed of 15000 rpm, the feed rate of 900 mm/minutes, step over of about 0.3 mm, and the typical insole product with a wide tolerance of 1.50 mm were recommended. The optimal machining time for the insole production for patient 1 is 3.79 hours and 4.03 hours for patient 2. The results of the optimum cutting parameters can be used in the real manufacturing process in CNC machines.

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