Simulation of manufacturing strategy of an orthotic boots shoe insole product with a Computer-Aided Manufacturing for club foot patient

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Abstract. In this paper, the design of orthotic boots in the club foot patient is investigated concerning the optimum condition of cutting parameters using computer-aided manufacturing. 3D CAD model insole is obtained from the scanning process until the design phase using reverse innovative design method. 3D CAD Model insole is designed using curve Base Modeling. From this design, simulated optimization can be obtained from Computer-Aided Manufacturing (CAM). Optimal manufacturing time optimization is simulated on the CNC Milling machine with the Taguchi approach. Six selected parameters containing toolpath machining, feed rate, spindle speed, depth of cut, Cutter selection, and insole dimension size are of particular interest. It is found that the design layout L2736 gives the most optimal simulation manufacturing using toolpath strategy tep and shallow finishing with spindle speed 1500 rpm, STEPD down 3 mm, Step over 2 mm, and 2mm Cutter diameter, on the model tolerance size 0.75 mm.

Keywords: club foot, CAM, PowerMill 2016, toolpath strategy

1. Introduction
Congenital talipes equinovarus (CTEV) or club foot is an abnormality in the form of legs that occur since birth or congenital but not yet known for certain causes of occurrence. This leg-Shape disorder occurs in 1-2 children from 1000 births. The condition involves musculoskeletal disturbances in the function of the joints, ligaments, nerve muscles, and tendons, as well as the spine. Early Prevention of this disorder is very difficult to do because it is congenital or genetically, but can be known early so that can be done further treatment. A person who has a form of the foot like this will feel the inconvenience of doing day-to-day activities so that every job or activity performed is less good and not maximally [1, 2]. The development of the shoe industry is currently running very quickly and rapidly, both in the design that is offered by man fabrication done [2, 3]. However, it cannot be enjoyed by some people who have a deformity foot disorder such as the foot of the Pengkor (Fig.
The foot of the club foot does not fit the shape of the footwear in general, resulting in a loss of comfort and will hurt the legs. Salah One factor of the convenience of footwear is located in the insole that comes into contact with the foot. This kind of condition has been reported by [3] on his paperboard stating that one of the factors of footwear comfort when used for daily activities is in the insole which is designed and manufactured according to the shape and size of the soles. The process of making insole with design by the shape and size of the foot should be used Reverse Engineering (RE) technology with Computer-Aided Design (CAD) base, Computer-Aided Machine (CAM), and computer Numerical Control (CNC) is reliable, and it is often referred to as Computer-Aided Reverse Engineering System (caresystem) [4 - 9].

Figure 1. Deformity foot sufferers feet

CARESystem has played an important role in manufacturing foot molds and custom foot orthotics components [1-3]. The availability of CAM software to facilitate CNC machines in making Ankle Orthotics (AFO) legs produces products with excellent dimensional accuracy, precision, and performance that is similar to making AFO with manual techniques [3]. Also, recent research shows that making AFO using a CNC machine produces products that are precision, comfortable, safe, accurate by the shape of the patient’s foot, and following orthopedic standards [4]. So far, 3D scanning tools, CAD, and CNC machines are the most suitable tools for designing many products because this system is easy to operate and affordable, and has exceptional clinical application in designing orthotic shoe insoles. The use of CAD in the shoe and sandals industry is needed because it can shorten the design time of new products for consumers and reduce product development costs [5]. At present, many CAD tools are available such as Inventor, SolidWorks, Power SHAPE, Art CAM, Toolmaker, CAD copy, and PS Mold Maker, which can help designers quickly create 3D models with precision, realistic, and consistent with 3D CAD models [6]. Besides, the availability of CAD software can help to design 3D insole models that lead to a shift in product development from physical models to digital ones or from the design of 2D drawing processes from 2.5 D / 3D image models [1, 6].

CNC is a machine manufacturing technology that is widely used in the industry. CNC machines are used to speed up the production process. CNC machines have Spindle speeds of up to 60,000 rpm. CNC is one of the modern technologies that increase efficiency, accuracy, and quality of workpieces compared to conventional cutting [10]. Estimation of machining time is an important step towards an optimal and practical production plan [11]. [12] Gavril (2016) states how to increase productivity and cost optimization in CNC manufacturing with a work time yield of 32.49% can reach an economic value of up to 10.33% for manufacturing costs. Parameter setting machining strategy toolpath in CAM can affect machining time [3, 7 - 9]. Machining toolpath strategy consists of speed, stepover percentage, feed rate, and tool trajectory strategy [13 - 15].
This paper presents the optimization of machining time of AFO insoles for club foot patients. Machining time for each variation is obtained by simulation using CAM PowerMill 2016 software and CNC machines. The optimal parameters from the machining process of orthotic insole shoes for club foot patients is also discussed in detail.

2. Material and methods
In this paper, patients with club foot type foot deformities are identified (Figure 1); 65 years old and have suffered foot disorders since birth. The condition of the patient’s right foot is seen twisting inwards where the patient’s feet are not a foothold when walking. While the patient’s left leg changes in bone structure due to being the main focus of the patient when standing. This becomes a difficulty for patients in carrying out daily activities. The SemiRID method is used in this paper, the initial process is carried out by forming a 3D replica of the foot using gypsum which is a physical model of the foot which will later be digitized by a scanning tool [3] This process was carried out because the geographical location of the patient was unable to be reached by the researcher when scanning. 3D implant technique is performed on the patient by molding the foot with white and blue gypsum material into the box (foam box shoe method) which is then processed further on the scanning tool to get 3D CAD Model feet in .STL format.

The output from the scanning process is in the form of a 3D model of the foot implant .STL format. The 3D foot implant model is then processed into the CAD PowerShape 2019e device to make 3D Curve Base Surface Modeling (CBS_Modeling) foot model and insole for patients. CBS_Modeling modeling was chosen because the foot contour curve can cover parts of the curve, curve boundaries, and roommate so that it can benefit the editing process of the curve formed and can get a smooth insole surface, as has been done by [3, 7 - 9]. This 3D model has then performed design variations by enlarging the foot geometry scale based on geometry tolerance as has been done by [3, 7 - 9]. 3D CAD model insole in club foot patients is shown in Figure 2, while the magnification size scale in the design is depicted in Figure 3 and Table 1.

![Figure 2. 3D Model CAD Insole : (a) Model Insole Shoes for Patient Clubfoot, (b) 3D Model Assembly Shoelast and Insole](image-url)
The optimal design of the Club foot insole model is obtained by performing Taguchi simulation-based optimization using CAM PowerMill 2016 software \cite{7-9}. The choice of machining strategy toolpath parameters is very important because it can reduce machining time \cite{7, 9, 16}. In this paper, 6 factors forming toolpath strategy are chosen, including Toolpath machining, feed rate, spindle speed, depth of cut, selection of Cutter, and dimensions of the insole. The response is measured as machine time in the CAM PowerMill 2016 simulation of each machining process. The process of making a toolpath strategy using CAM PowerMill 2016 software can be seen in Figure 5. The final result of this paper is a 3D CAD insole design model (Figure 2), geometrical variations of the two products based on the tolerance set in the direction of sb X and Y (Figure 3, and table 1), Optimal Toolpath Strategy, and machining time (Table 3).

| Tolerance (mm) | Left Foot Patient Club Foot without Material Added | Right Foot Patient Club Foot without Material Added |
|----------------|---------------------------------|---------------------------------|
|                | Lenght of ISO (A) | Wide of ISO (B) | High of ISO (C) | Lenght of ISO (A) | Wide of ISO (B) | High of ISO (C) |
| 0              | 245.94            | 109.13           | 35.03           | 172.91            | 97.22           | 42.42           |
| 0.75           | 246.69            | 110.14           | 35.03           | 173.48            | 98.06           | 42.42           |
| 1.5            | 247.44            | 111.65           | 35.03           | 175.58            | 99.85           | 42.42           |

Figure 3. Magnification of tolerance scale on club foot insole

Table 1. Magnification of The 3D CAD Model Insole Size
Figure 4. (a) 3D CAD insole clubfoot, (b) Material size settings in PowerMill 2016, (c) Cutter settings, (d) Input parameters on toolpath strategy, (e) Toolpath Model Area Clearance (roughing), (f) Toolpath Raster finishing (Semi-Finishing), (g) Toolpath Step and Shallow (Finishing), (h) time of machining process simulation, (i) Simulation results of AFO products for clubfoot foot disorder patients, (j) NC Machining Code

Table 2. Machining parameters

| Code | Factor       | Level                  | 1       | 2       | 3       |
|------|--------------|------------------------|---------|---------|---------|
| A    | Toolpath     | Raster Finishing       |         |         |         |
|      |              | Optimaized Constants Z|         |         |         |
|      |              | Step and Shallow       |         |         |         |
| B    | Spindle Speed| 10000                  | 13000   | 15000   |         |
| C    | Stepdown     | 5                      | 3       | 2       |         |
| D    | Stepover     | 4                      | 3       | 2       |         |
| E    | Cutter       | 6                      | 4       | 2       |         |
| F    | Tolerance    | 0                      | 0.75    | 1.5     |         |
Table 3. Machining Time Based on S / N Ratio

| No | Toolpath       | Spindle Speed | StepDown | StepOver | Cutter | Tolerance | Waktu Simulasi (minutes) | Waktu real (minutes) |
|----|----------------|---------------|----------|----------|--------|-----------|--------------------------|----------------------|
| 1  | Raster Finishing | 10000         | 5        | 4        | 6      | 0         | 160                      | 200                  |
| 2  | Raster Finishing | 10000         | 5        | 4        | 4      | 0.75      | 167                      | 209                  |
| 3  | Raster Finishing | 10000         | 5        | 4        | 2      | 1.5       | 186                      | 233                  |
| 4  | Raster Finishing | 13000         | 3        | 3        | 6      | 0         | 150                      | 180                  |
| 5  | Raster Finishing | 13000         | 3        | 3        | 4      | 0.75      | 158                      | 198                  |
| 6  | Raster Finishing | 13000         | 3        | 3        | 2      | 1.5       | 195                      | 244                  |
| 7  | Raster Finishing | 15000         | 2        | 2        | 6      | 0         | 152                      | 190                  |
| 8  | Raster Finishing | 15000         | 2        | 2        | 4      | 0.75      | 162                      | 203                  |
| 9  | Raster Finishing | 15000         | 2        | 2        | 2      | 1.5       | 188                      | 235                  |
| 10 | Optimized Constants Z | 10000   | 3        | 2        | 6      | 0.75      | 151                      | 189                  |
| 11 | Optimized Constants Z | 10000   | 3        | 2        | 4      | 1.5       | 201                      | 251                  |
| 12 | Optimized Constants Z | 10000   | 3        | 2        | 2      | 0         | 231                      | 289                  |
| 13 | Optimized Constants Z | 13000   | 2        | 4        | 6      | 0.75      | 172                      | 215                  |
| 14 | Optimized Constants Z | 13000   | 2        | 4        | 4      | 1.5       | 183                      | 229                  |
| 15 | Optimized Constants Z | 13000   | 2        | 2        | 2      | 0         | 194                      | 243                  |
| 16 | Optimized Constants Z | 15000   | 5        | 4        | 6      | 0.75      | 179                      | 224                  |
| 17 | Optimized Constants Z | 15000   | 5        | 3        | 4      | 1.5       | 168                      | 210                  |
| 18 | Optimized Constants Z | 15000   | 5        | 2        | 2      | 0         | 183                      | 229                  |
| 19 | Step and Shallow  | 10000         | 2        | 4        | 6      | 1.5       | 181                      | 226                  |
| 20 | Step and Shallow  | 10000         | 2        | 3        | 4      | 0         | 192                      | 240                  |
| 21 | Step and Shallow  | 10000         | 2        | 2        | 2      | 0.75      | 215                      | 269                  |
| 22 | Step and Shallow  | 13000         | 5        | 4        | 6      | 1.5       | 211                      | 264                  |
| 23 | Step and Shallow  | 13000         | 5        | 3        | 4      | 0         | 219                      | 274                  |
| 24 | Step and Shallow  | 13000         | 5        | 2        | 2      | 0.75      | 232                      | 290                  |
| 25 | Step and Shallow  | 15000         | 3        | 4        | 6      | 1.5       | 244                      | 305                  |
| 26 | Step and Shallow  | 15000         | 3        | 3        | 4      | 0         | 252                      | 315                  |
| 27 | Step and Shallow  | 15000         | 3        | 3        | 2      | 0.75      | 269                      | 336                  |

3. Results and discussions

Clubfoot or congenitally deformed leg (CTEV) was introduced by Hippocrates around 300 BC. He described two forms of clubfoot, namely innate and acquired during infancy. The term talipesquinovarus comes from the Latin words: talus (ankle), and pes (foot); equinus: "like a horse" (heel plowed flexion), and Varus: inverted and adducted. The incidence of innate talipes quinovaruse is around 1-2 per thousand live births. This is one of the most common birth defects involving the musculoskeletal system [17]. The shape of the foot of the clubfoot sufferers is not following the shape of the footwear in general, which results in loss of comfort and will hurt the foot. One factor supporting the comfort of footwear lies in the insole that is in direct contact with the sole [2, 3]. The process of making custom insole for clubfoot sufferers starts from the scanning stage up to manufacturing the insole in a CNC machine. Optimal insole products in this paper, later obtained through CAM-based manufacturing optimization on CNC machines. Here some manufacturing simulations are carried out with treatments determined based on the Taguchi method. The optimal insole manufacturing design layout in this paper is determined as orthogonal array (OA) L2736 (Table 3). The initial parameters included in OA are presented in Figure 3, and Table 1-2. The response measured in this study is the time to work on the simulation and the time to work real (Table 3).

3D insole images for club foot patients were designed using CBS modeling techniques [7, 19]. CBS_Modeling modeling was chosen because the contour curve in the club foot patient's legs includes the curve, the curve boundary, and the roommate. This can directly provide a significant advantage in the editing process of the curve being formed and obtaining a smooth insole surface, as has been done by [7 - 9] Anggoro, et al. [2017; 2018; 2019] in designing insole for patients with deformity foot diabetes Mellitus. 3D CAD Model in Figure 2 is what design variations are carried out by enlarging the scale of the foot geometry based on geometry tolerance (Figure 3, and Table 1). the three design variations (0, 0.75, and 1.5) will later be processed into the CAM PowerMill 2016 software for the manufacturing process of machining toolpath strategy. The variations in the
geometry of the product design are based on tolerances determined by magnification of the scale in the X-axis and Y-axis direction.

The 3D CAD Model in Figure 2 is then imported into CAM PowerMill 2016 for manufacturing simulation optimization. This process begins by selecting the optimal machining cutting parameters in the CNC machine. There are six parameters used (table 2) to work on orthotic insole shoes for clubfoot patients. Based on the Taguchi method, of the six factors, the OA L2736 design layout will be obtained. Here 27 experimental treatments are needed in the process of manufacturing insole on a CNC milling machine. The use of the Taguchi method in this paper is done to avoid the selection of treatments that produce suboptimal responses. Each treatment shows the toolpath strategy used in each work by predetermined cutting parameters. The use of CAM software in this paper is done to avoid error errors in the manufacturing process (trial and error). The final output of CAM PowerMill 2016 is the NC-Code which is used to run programs on CNC machines.

NC-Code is created by making machining parameter data such as Toolpath Strategy, Spindle speed, Step down, Step over, and Cutter diameter used for working on club foot patient insoles. The toolpath strategies used include Raster Finishing, Optimized Constant Z, and Step and shallow. These machining parameters were selected referring to research conducted by [7 - 9] and succeeded in optimizing the processing time of orthotic Ankle foot machining for diabetic patients. The most optimal simulation time for each treatment in OA L2736 in this paper is the fastest execution time with the simulation results by the 3D CAD Model insole of Club foot patients. The stages of the optimization process of orthotic insole shoe manufacturing in CAM PowerMill 2016 according to the specified OA can be presented in Figure 4. This machining time simulation yields a value of 25% less than the actual machine time as explained by the CAM-CNC engineer. The working time in this paper is the sum of the time from the Roughing process to the Finishing process (when the cutter starts from zero points until the cutter returns to the toolpost and 3D Insole models are formed which are presented in Figure 6). The biggest influence in setting toolpath strategy on PowerMill 2016 lies in the spindle speed and maximum framed feed rate (100%) as described by [9, 18] also found that there is a deviation of the simulation time with the actual engine time due to the time needed for cutter replacement in a CNC machine, and setting the material to the machine table.

The fastest machining time simulation results in this study are Raster Finishing toolpath strategy with a spindle speed of 13000 rpm, step down 3 mm, step over 3 mm, and by using a cutter diameter of 6 mm, at a tolerance size of the model 0 mm by 150 minutes. While the longest time is in the cutting conditions: step and shallow finishing toolpath strategy with spindle speed 1500 rpm, step down 3 mm, step over 2 mm, and cutter diameter 2 mm, at a tolerance size of 0.75 mm model of 269 minutes. The ratio of processing time between the two toolpaths is 56%. This happens because the cutter movement in the Step and shallow finishing toolpath strategy is more complex when compared to the raster finishing toolpath strategy (Figure 5). This results in simulation results on the Step and shallow toolpath strategy closer to the 3D CAD profile of the insole model according to the physical model of the patient’s foot (Figure 6), when compared to the raster finishing toolpath strategy.
Figure 5. Machining toolpath strategy; (a) Raster Finishing, (b) Optimized Constant Z, (c) Step and Shallow Finishing

Figure 6. Simulation Results using PowerMill 2016: (a) Raster Finishing, (b) Optimized Constant Z, (c) Step and Shallow Finishing

From Figure 6 it can be seen that the visuals from the 2016 PowerMill simulation (Figure 6c) are smoother when compared to the other two finishing toolpaths. In the Raster Finishing toolpath strategy, and Optimized Constant Z there are still cutter trajectory marks (red marks), if machined the cutter trajectory process is formed which can affect surface smoothness and disturb the contours of the insole for club foot patients (Figure 2a). In real terms, this condition will affect the patient's comfort in using insole (Figure 2b). Surface smoothness and contour are important factors that provide a sense of comfort, safety, and suitable for patients with leg defects [3]. So that the optimum processing time for insole shoes in this paper is 269 minutes. This time can be reached where the cutting parameters are in the conditions: Toolpath Strategy step and shallow Finishing, Spindle Speed 1500 rpm, step down 3 mm, step over 2 mm, and diameter cutter 2 mm, on the tolerance size of the model 0.75 mm.

4. Conclusion
The design varied by changing the product definition of the parameter and a new design of insole shoe orthotics for the patient with club foot can be optimized by a CAM simulation. Optimal processing time for simulations with conformity to 3D CAD Model insole for club foot patients in this paper results from cutting parameters under conditions: toolpath strategy Step and shallow finishing, Spindle Speed 1500 rpm, step down 3 mm, step over 2 mm, and diameter cutter 2 mm, the tolerance size of the model is 0.75 mm. The fastest simulation time is 269 minutes. These valuable data are needed for the real manufacturing process of insole material in CNC milling.

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