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DYNAMIC FEED RATE IN MULTIPLE INDEPENDENT SPINDLES CNC MILLING MACHINE FOR ORTHOTIC INSOLE MANUFACTURING

Pongpun Watasuntonpong, Monsak Pimsarn and Akapot Tantrapiwat

Department of Mechanical Engineering
Faculty of Engineering
King Mongkut's Institute of Technology Ladkrabang
1, Chalongkrung Road, Ladkrabang, Bangkok 10520, Thailand
p.watasuntonpong@gmail.com; monsak.pi@kmitl.ac.th

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Abstract. *Diabetic foot ulceration can be prevented in case of the high plantar pressure being reduced and transmitted from ultimate stress point to the total area of plantar tissues. Custom-Made Insole (CMI) is one of the practical techniques to reduce ultimate stress on the patient's foot. By employing the CAD/CAM technology, CMI for diabetic patients can be made fast and cost effective in comparison to the conventional method. In this research, there were two major improvements which made the CMI manufacture even faster and cheaper. First, a foot sole surface impression machine was developed to be compatible with the CMI configuration. The reusable foot sole impression machine can replace the traditional dispensable impression foam. An experiment was carried out to verify that pressure distribution on the impression surface was effective and comparable to the conventional method. The second improvement was the implementation of multiple independent spindles CNC system on the CMI cutting process. The configuration of multiple cutting tools and design cutting paths were investigated. In addition, the optimum cutting parameters were established using cutting force criteria. The relationship between cutting force and axial depth of cut was used to assign the feed rate. Because the feed rate which relates to the Z-direction can be varied among all spindles, two different techniques, fixed and dynamic feeds, were applied and compared. On average, the fixed feed technique can cut a pair of insole within 32 minutes, while dynamic feed can produce within 29 minutes. Overall both foot sole surface impression machine and multiple independent spindles CNC milling machine can cut down the production time to only 60% of the time used in typical CAD/CAM system, and 20.8% of the time used in conventional method.*
Keywords: Custom-Made Insole (CMI), Foot sole surface impression machine, Multiple independent spindles, CAD/CAM

1. **Introduction.** Diabetes mellitus, known as diabetes, is a lifelong condition or chronic disease that affects the body's ability to use the carbohydrates and glucose, in which the body fails to control the blood glucose level in the range of 90-140 mg/dl [1]. This chronic disease is associated with dysfunction and failure of organs, especially for the kidneys, eyes, heart, blood vessels and nerves. Long-term complications include peripheral neuropathy, ischemic and infections, which are the principal etiology factors of foot ulcerations [2,3]. Diabetes mellitus patients have grown around 415 million people and up to 592 million in 194 countries by 2035 [4]. In Thailand where this research was carried out, the number of DMs is around 3.5 million in 2009 and up to 4.7 million by 2017 [5]. World Health Organization (WHO) announces that diabetes mellitus is the 7th leading cause of

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death in 2030 [6]. Diabetic neuropathy is caused by foot lesions. Approximately, 15-25% of the diabetes patients have approximately developed to the lower extremity-ulceration [7]. These ulcers frequently become the infection and caused the lower limb-amputation [8]. Foot ulceration of diabetics can be prevented and treated in the case of the high plantar pressures being reduced and transmitted from ultimate stress point to total area of plantar tissues by the off-loading prevention technique [9,10]. Custom-Made Insole (CMI) is one of the practical techniques to increase the total contact area and to reduce ultimate stress between the foot and insole [11,12]. CMI is usually conformed to individual foot shape and can accommodate the unique foot structure and pathology which was produced to match between insole surface and the contours of the feet. Nowadays, CMI production has been developed using different techniques. In hospital or infirmary, CMI is conventionally produced by skilled medical physicians. In Thailand and several other countries, CMIs are still made by a sequence of traditional casting mold technique and the thermal vacuum forming method known as the conventional method. The average processing time of this method is 6 hours per one pair of CMI. This is considered a time-consuming process, and also resulting in costly production. In addition, the old techniques also cause difficulties on imprint errors, mold shape modification, and technician expertise training [13-15]. In recent years, the Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) system has been introduced for manufacturing foot orthoses. The first CAD/CAM system for manufacturing CMI was established and introduced by American digital technology (Orthocan) in 1988 [16].

Currently, there had been many techniques and fabrications involving custom designs and manufacturing using Rapid Prototypes Technology. Free Form Thick Layered Object Manufacturing (FF-TLOM) Technology [17] was proposed for cutting materials, such as, foam and elastomer. However, this technique is unsatisfied for tough polyurethane foam as material of CMI. Hotwire cutting system for Variable Lamination Manufacturing (VLM) [18,19] was favorably built as another technology, but it was not a proper technique due to the thermal properties of EVA foam. In 2009, another technology is the non-weight bearing scanning technology and the rapid prototyping systems were employed to increase the production of CMI [20]. With these novel techniques, a pair of insoles can be made within couple hours which are the significant improvement of the production time. Nonetheless most of these previous works were done by the typical CAD/CAM technology, only the material and the model were changed. With these accessible technologies, in Thailand, one pair of CMI is made at the cost about \$100-150 which was almost equivalent to half of the average monthly labor income in the nation. It was still considered very expensive, and many diabetes patients cannot afford it. This price is based on data in 2012 when this research started. The motive to improve the CMI manufacturing process was to bring down the production cost which depends on several factors but mainly on the production time.

In this research an enhanced system of CMI manufacturing process has been improved from imprinting patient feet to producing the EVA insoles. The outcome was a great improvement from the typical CAD/CAM technique. To reduce the materials used in the process of foot sole shape, a foot sole surface impression machine was developed. To increase the production rate, three independent spindles CNC machine was invented based on the insole cutting configurations. However, the multiple independent spindles system had led to additional challenges which are unavailable post-processing software, tool path planning and feed rate control. While the cutting parameters of a single spindle depend on the one spindle, the multiple independent spindles system requires more complicated consideration on the cutting feeds and depths especially when cutting soft material such as the EVA foam. The optimum cutting parameters for all spindles can lead to the improvement of production time and workpiece quality. All these parameters were used in the dynamic feed rate method which was a new approach in this research.

There were few achievements made in this research that dedicate to the overall improvement of the CMI manufacturing process. This paper has presented them in sections according to the process sequence. In the following section, an invention of foot sole surface impression machine and how the 3D foot sole image was made is explained in detail. Because the imprinted foot soles were made by the aim to distribute contact stress over the entire surface, the evaluation of stress distribution result is also presented in this section. In the third section, the multiple independent spindles CNC machining system is introduced. The details of its configurations, both hardware and software, which were designed to fit with the CMI cutting process are explained. In addition, the relationship between cutting path planning and the machine configurations in different cases are established and shown. With the multiple spindles, CMI cutting had become more complicated with several cutting parameters involved. The process to determine optimum cutting parameters is revealed in the fourth section. This is where the dynamic feed rate technique for multiple independent spindles was established to maximize the production rate. In the fifth section, the CMI cutting result using dynamic feed rate technique is presented in comparison with other methods. Not only the production time, but also the quality of the outcome insole is discussed in this section. Finally in the last section, the improvement of CMI manufacturing in this research is concluded.

2. **Foot Sole Surface Impression Machine and 3D Image Conversion.** In order to imprint the foot profile for CMI manufacturing, the foot sole shape has to be formed in the state of full weight bearing impression footprint. In traditional methods, a block of impression foam, which made out of a type of phenolic foam, is commonly used. This type of material is costly and dispensable. To imprint a foot on this foam, the skill physician has to be careful. If the patient moves or turns the foot during the operation, the foot imprint shape will be distorted, and that foam block has to be discarded. Once the foam is imprinted, it is used as an opposite mold to make the plaster model of the patient's feet. This plaster casting takes about three to four hours, and then it is carefully carved to fit with the desired insole profile. This process requires a skilled technician and is time consuming. In addition, the plaster models are heavy and need storage for future use. To overcome these limitations, a foot sole surface impression machine has been developed to imprint the foot sole into 3D computer model.

The foot sole surface impression machine can capture the foot sole in the full weight bearing state same as the traditional method, but it is reusable and has low operating cost. The foot shape imprinted on the machine can be scanned by inverse engineering method, and the data is stored in digital format which is easy for modification and relocation. It provides great benefit as the patient foot imprint can be obtained in remote places. Then the foot data can be conveniently sent to a CMI manufacturing plant anywhere in the world. This foot sole surface impression machine is utilized the principle of particle vacuum mold forming. It comprises of a bucket filled with small round plastics pellets about 0.1 mm in diameter. Over the surface of pellet mass on top of the bucket, a thin rubber sheet with the thickness of 0.5 mm is covered and sealed to enclose the bucket. In the bottom, it is connected with air tubes to a vacuum pump. Figure 1(a) shows a diagram of major components of the foot sole surface impression machine. The machine operates by a simple controller which directs the vacuum pump to generate negative pressure in the vessel storage. In the normal state, the controller turns solenoid valve-A to open and closes valve-B. In this state, the imprinting box is not subjected to the vacuum pressure, and therefore the plastic pellets inside the box can move freely. When imprinting a foot over the rubber sheet, the foot sole surface can be formed similar to walking on the sand. In this state the plastic pallets can still move freely according to the foot profile. When capturing the foot sole profile, the controller closes solenoid valve A and opens valve B, charging vacuum pressure into the imprinting box. This vacuum force causes all the plastic pallets to clench on one another, and restrains their movements. After that, the foot can be removed from the box, and the negative foot profile is temporarily captured onto the machine. To return to the normal state, the controller closes valve B and opens valve A again. This removes the vacuum pressure in the system, and the plastic pellets can now move freely again. The level of vacuum pressure which holds the foot sole profile is monitored by a pressure sensor. Usually it was set at 0.5 bars. A lower vacuum will result inadequate holding force, but higher vacuum causes more operating time and power consumption. Figure 1(b) shows the foot sole surface impression machine was in an actual operation. The captured foot profile was then scanned by a 3D scanner which can produce cloud point data of the foot sole. This data was later converted to foot sole 3D model by using the SENSE 3D scanner and it was recorded in STL format. After that the foot imprinted model was converted into the insole profile using the Autodesk OrthoModel 2016 Pro program [21]. This software can adjust the foot profiles to match the typical insole configuration and also the outer perimeter. At this point the 3D CMI model is ready for the CMI manufacturing by a CNC cutting system.

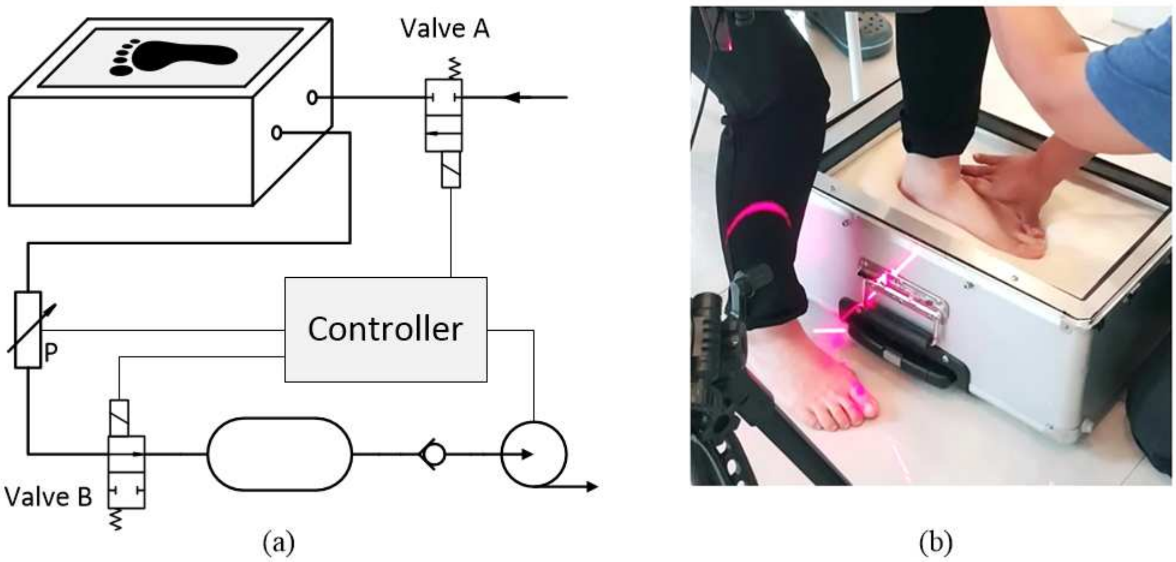

Figure 1. (a) The diagram of major components of the foot sole surface impression machine and (b) the foot sole surface impression machine

In order to compare the foot sole shapes obtained between the traditional method and this new foot sole surface impression machine, the 3D scanned models were acquired from both models and analyzed using the Geomagic Qualify 12 program [22]. By overlaying one model over another, the differences of the two profile surfaces were measured along certain directions which relate to the most bearing pressure spots on the foot sole. These directions are shown in Figure 2(a). They are labelled from A to D, where A is the maximum foot length, while B, C and D are the metatarsal cross widths at a quarter, a half and three quarters of the foot length measured from the toe, respectively. The maximum differences between the two models along A, B, C and D directions were 4.3 mm, 3.2 mm, 4.0 mm and 2.1 mm, respectively. Although these values seem to be significant comparing to the typical thickness of the insole, both models were very similar in term of the profile

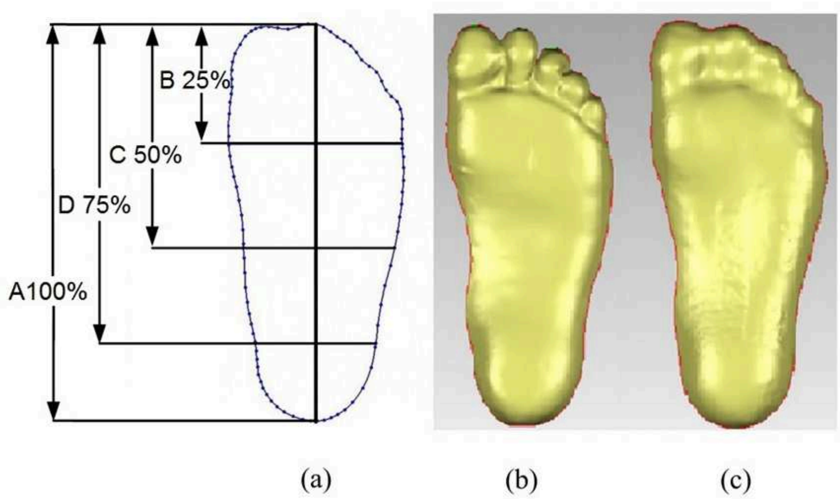

FIGURE 2. (a) The geometric data are defined to 4 parts (A, B, C and D), (b) the scanned footprint of impression foam and (c) the scanned footprint of foot sole surface impression machine

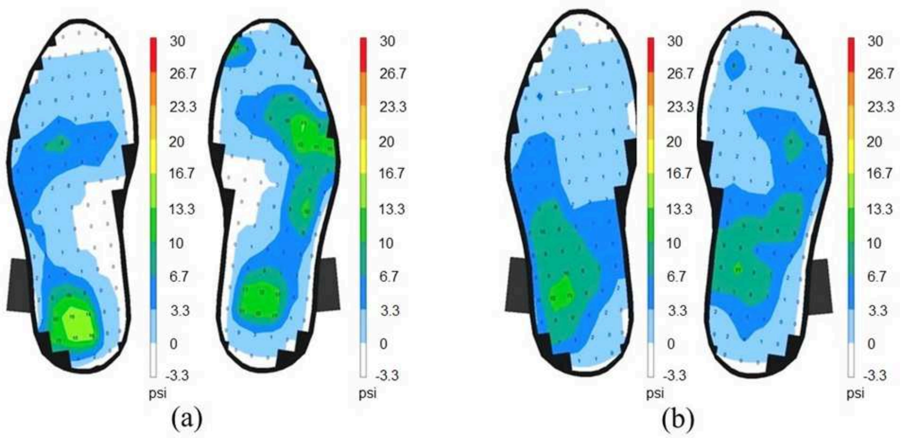

FIGURE 3. (a) The stress distributions of the foot soles captured from a flat surface support and (b) the stress distributions from the impression machine

shape. It means that the distribution of the stress between the bearing foot and insole is unlikely depending on position of the foot but rather the entire profile. In another word, the insole can be thicker or thinner as long as it has a right profile. The true purpose was to distribute concentration of stresses over the foot sole. To verify the capability of stress distribution by this machine, a series of test was carried out on 24 volunteers, ranging 49-89 kg in weight. By placing a force sensor pad, Prosthetic Mat from FSA, on the impression surface during imprinting the foot sole, the stress distribution can be achieved. Figures 3(a) and 3(b) show the stress distributions of the foot soles captured from a flat surface support and the impression machine support. In this particular patient case, the result has shown that the maximum stress was dramatically reduced from 130 to 92.5 kN/m^2 because the foot sole contact area had increased by 20.5%. Even though the stress distribution is highly dynamic depending on how the person stands or leans on both feet, the comparison has indicated that the stress distribution performance by this machine was effective.

3. Multiple Independent Spindles System. Another improvement in this rapid CMI manufacturing is the implementation of the multiple spindles CNC machine. Normally, the multiple spindles milling machines are designed to increase the production rate for mass manufacturing. By adding multiple spindles to the same z-axis, multiple workpieces can be made simultaneously. This method is not suitable for making CMI which is the individual customized product for different patients. To implement the multiple spindles concept, each particular spindle is capable of moving independently on the vertical z-axis, and they divide the working areas from the entire insole. This research has proposed the design and fabrication of such system which is configured for the CMI manufacturing.

This multiple independent spindles CNC machine basically allows all spindles to move and engrave independently in the vertical axis. The configurations of the machine are based on the Router type milling machine which has the working table moving along the y-axis, x-axis, and z-axis. Figure 4 shows the multiple independent spindles CNC machine which was successfully developed and tested during this research. The machine is driven by step motors through a set of ball screws. The machine working area is 300 mm by 300 mm by 150 mm which is well matched with the designed area for the typical foot size by the statistic, maximum 297 mm in length (size 13 US or size 46 Europe). The working table can move with maximum feed rate up to 1500 mm/min. Because the material of CMI is EVA foam which requires small cutting force, the machine has 500 W 100 VDC motors for each spindle with individual air cooling fan. This motor has maximum torque 0.55 N-m and the rotational speed of 12000 rpm.

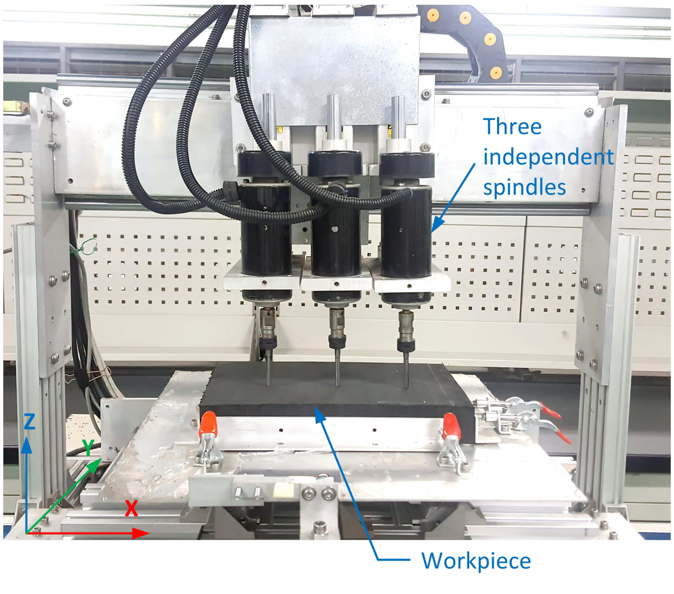

FIGURE 4. The first prototype CMI cutting machine with three independent spindles

The machine is controlled by the open source software, MACH3 program, which has been modified to collaborate with the extra spindles. The MACH3 is widely used with typical milling CNC machines. This software is under the GNU, General Public license. It has also led to proprietary low cost PC based controller, providing an affordable CMI manufacturing system that can be great beneficial for many diabetic patients who cannot afford the expensive custom insole. The MACH3 in this research was developed based on the Windows OS platform. The maximum capacity of the original version contains 5 axes, which are X, Y, Z, A and B axes. Usually, the A and B axes are the angular coordinates around X and Y axes, respectively. To make the software accessible with the multiple independent spindles CNC machine, the A and B axes were used to drive the additional linear spindle feeders. With these configurations, the standard MACH3 is capable of controlling all three spindle feeders. Although the additional spindles can share the work load, the performance of the machine is highly depending on how to assign the offset distance between these spindles.

All spindles were connected in X and Y directions. Those several patterns can be planned to complete the cutting area. There were two types of tool path suitable of this machine configuration, y-zigzag and x-zigzag patterns. The y-zigzag is the path where the tool cuts along the y-axis until the end of the workpiece width, later it moves in x-axis for the step over size which is usually 100% of a tool diameter. The tool repeats the cut again in the same manner until the x-direction cut proceeds through the spindle offset length. For the x-zigzag the tool path is similar with the y-zigzag, except that the movements are in the opposite direction. These zigzag patterns take turns to cut in both Conventional and Climb cut directions. However, due to the soft material used for CMI, the Conventional and Climb cuts were insignificantly different. To select the suitable pattern, the feed rate was rather taken into account. All spindles are driven by the x-axis feeder, while the light weight workpiece moves along with the y-axis due to the Router-Type machine configuration. It means that the x-axis feeder motor has to drive much heavier load and requires low cutting speed for the same power capacity. The x-axis feeder also works fewer times on the same cutting area for the zigzag in y-direction. Therefore, the y-zigzag style was chosen to minimize the cutting time.

The number of spindles and their offset distances are the most crucial factors of cutting time reduction. The cutting depths of all spindles are typically assigned from the top surface of workpiece as the axial depth of cut. The CMI is normally made of soft material, which is 20 mm thick. To determine the cutting time, the step over size at 100% of the tool diameter was used throughout the cut. The spindle offset defines the size of the pocket length which should be the common multiplication of the total workpiece length. If the spindle offset is not exactly the common multiplication, it will result in cutting of a fraction area, and some spindles might have to run empty without the cutting. Therefore, the pocket length, L_p, can be determined using

$$L_p = N_s L_s \tag{1}$$

where N_s is the number of spindles, L_s is the spindle offset distance between each spindle. When the pocket length is equal to the length of total working area, it means that there is only one pocket cut for the entire operation. In this case the spindle offset distance is equal to the length of the workpiece divided by the number of spindles. If the pocket length is the exact common multiplication of the workpiece length, the operation time is almost the same as in the first case. The difference is only the motions from one pocket to another, but it is very small in comparison to the operating time. In general, if there is a fraction area presented, the total workpiece length can be stated as follows.

$$L_w = N_p L_p + L_e \tag{2}$$

where L_w is the length of the working area, and N_p is thenumber of pocket, L_p is the length of pocket and L_e is the length of the fraction area. To calculate the total cutting time, in the case of $L_p > L_e > L_s$, the cutting time of fraction area will be equal to the cutting time of the whole pocket section. Giving N_c as the integer number of cutting paths along the perpendicular direction of spindle row, it can be determined by

$$N_c = \min\left\{ n \in Z \,\middle|\, n \geq \frac{L_s}{S_v} \right\} \tag{3}$$

where Z is the set of integers, and S_v is the step over size. In such case the total x-y traveling time, T_t, can be calculated as follows.

$$T_t = [N_p + 1] N_s \left[\frac{[N_c W_p] + [L_s - S_v]}{F} \right] \tag{4}$$

where W_p is the width of the cutting paths along the perpendicular direction of spindle row and F is the feed rate.

In the case of $L_e < L_s$, the fraction area does not require the full number of cuts same as in the first case. Giving N_e as the integer number of the fraction cutting paths, it can also be defined as follows.

$$N_e = \min \left\{ n \in Z \middle| n \geq \frac{L_e}{S_v} \right\} \tag{5}$$

and so the total x-y traveling time in this case can be calculated as

$$T_t = N_p N_s \left[\frac{[N_c W_p] + [L_s - S_v]}{F} \right] + \left[\frac{N_e W_p + [L_e - S_v]}{F} \right] \tag{6}$$

Figure 5 shows the diagram of multiple spindles cutting paths with all parameters which are related to the x-y travel of the tool. According to this cutting path analysis and the typical dimension of CMI cutting block mentioned early, the optimum spindle offset was set at 70 mm. This configuration is based on the y-zigzag pattern as already discussed early. It can be noted that these planning paths are only considered on the top projection area of the insole surface, i.e., x and y-directions. However, each spindle has to travel along the z-direction independently, and the actual feed has to be calculated according to the z-axis travel as well.

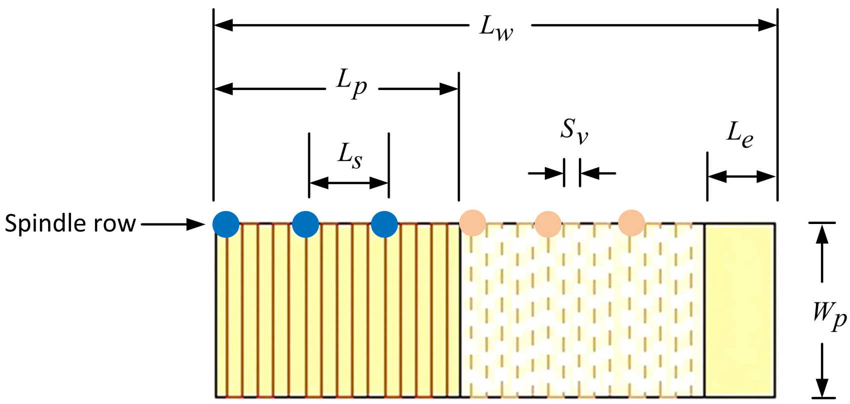

FIGURE 5. The definition of each parameter in the working area of y-zigzag pattern for calculating the total cutting time

It can be noted that all equations above were established based on possible cases in the multiple spindles configuration. They also show that the relationship between the spindle offset distance, the size of workpiece, the diameter of cutting tool, and the cutting plan has a great impact on the cutting time. The goal was to eliminate the fraction area in the cutting path planning and use the biggest tool diameter. However, some factors may be constrained such as the minimal spindle offset distance due to the size of the spindles, and limited cutting force due to the tool size. Using these relationships, the multiple spindles CNC machine was designed to have offset distance between each spindle at 70 mm as already mentioned early. There is only one pocket cut without fraction area in this configuration. Moreover, the use of 6 mm tool diameter requires 12 passes of cut at step over size equal to the tool diameter. With these configurations, the multiple spindles CNC machine was able to reduce the cutting time about one third of the time used in the typical system. In addition, other cutting parameters were assigned not only by the equations above, but also based on the properties of the material and cutting nature that are discussed in the next section.

4. **CMI Optimum Cutting Parameters.** During the CMI cutting, the most restricted factor which determines feed rate is the cutting force. Because the EVA foam, the main material used in CMI, is relatively soft, large amount of cutting force would result in high deflection of the material while cutting. Not only causing the cut surface to be rough, but also the outcome insole is inaccurate especially in multiple spindles where the cutting force from all spindles is acting on the material block at the same time. The cutting force also increases when cutting with a ball nose end mill. This is due to the small rake angle of the typical ball nose end mill. Because the insole surface is curved and continuous, regular ball nose end mills should provide minimum surface roughness characterized by the lay of tool paths. However, with many trials on different cutting tool shapes and sizes, the straight flute end mill has shown the best result in terms of low cutting force and the workpiece quality. To analyze the surface roughness caused by the lay of cutting tool, the insole cross section profile in relationship with the cutting tool path can be modeled as shown in Figure 6. It should be noted that this diagram has an exaggerated scale of the insole surface curvature and the tool diameter. By using the cosine function, the surface roughness, R_a, can be estimated as

$$R_a = \frac{1}{2}\sqrt{4R^2 + d^2 + 4Rd\sin\theta} - R \tag{7}$$

where R is the insole surface arch radius, d is the cutting tool diameter, and θ is the angle of tool point tip location measured from the vertical axis. In this relationship, at any particular tool diameter, the smaller R and the bigger θ will result larger roughness. For typical insole profile, R is usually more than 50 mm, and θ is less than 30°. With these values, the optimum tool diameter was found to be 6 mm, and it produced about 1.5 mm of the maximum R_a which is the roughness of the lay. Smaller diameter will result in smaller lay, but the cutting time will also increase as the tool has to cut many more passes. The biggest surface roughness usually occurs at the medial arch of the foot especially in claw feet. Later a test was made to show that the increment of pressure distribution was not significant on the insole cut by the 6 mm tool diameter.

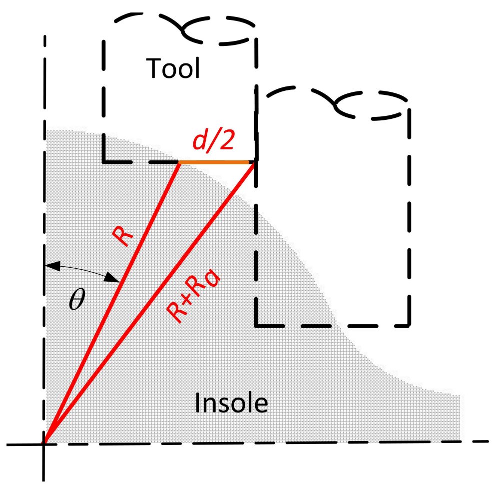

FIGURE 6. The roughness of lay produced by the cutting tool

After the optimum tool diameter was established, the amount of cutting force was mainly depending on the remaining three parameters, the feed rate, the step over and the depth of cut. To narrow down the variety, the step over size was assigned to 100% of the tool diameter. Later, a set of experiments was carried out in order to monitor the cutting force on the EVA foam. In the experiment, feed rates were set at 300, 600, 900, 1200 and 1500 mm/min and the axial depth of cut were 5, 10, 15, and 20 mm. The cutting forces were measured using a load cell which was installed at a coupling table. Figure 7 shows a diagram of the experimental setup. The cutting force was monitored in the y-axis which is the primary cutting direction. Several blocks of EVA foam with the length of 100 mm were cut, and the cutting forces were recorded by a data logger. The average cutting forces which relate to axial depth of cut are shown in Figure 8. It should be noted that these measurements were carried out on a single spindle.

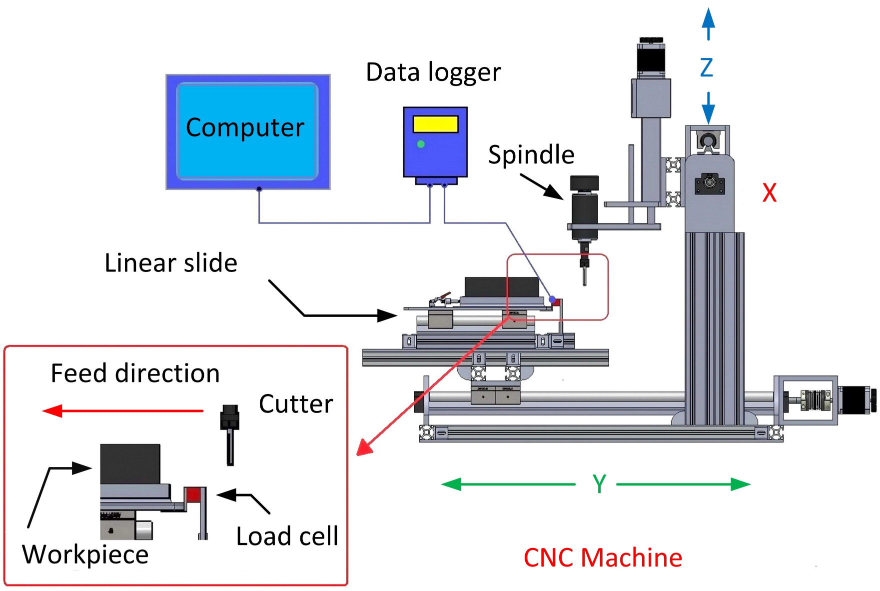

FIGURE 7. Diagram of cutting force measurement setup

In order to establish the relationship between cutting force and the workpiece quality, all workpieces from the cuts were measured for dimensions and surface roughness. The results have shown that the cutting force should not exceed 38-41 N for all depth of cut and feed rate. When considering case by case, at the lowest axial depth of cut, 5 mm and the spindle can travel at highest speed the machine can do, i.e., 1500 mm/min without any significant dimension error or poor surface quality. When increasing the axial depth of cut to 10 mm, the highest feed that could be assigned was about 1200 mm/min. As for the deepest axial depth of cut at 20 mm, the allowed maximum feed rate was reduced to 300 mm/min before the cut surface became very poor.

Using the result from the experiment stated above the cutting force criteria were set to 40 N. By replotting the data from the experiment, Figure 9 shows the relationship of the feed rate versus the axial depth of cut, and they are relatively linear. A linear regression for this relationship can be written as follows.

$$F = 1924.5 - 83.04d \tag{8}$$

d is the axial depth of cut and F is the feed rate which will be chosen for highest production rate in the multiple spindles system during the CMI manufacturing.

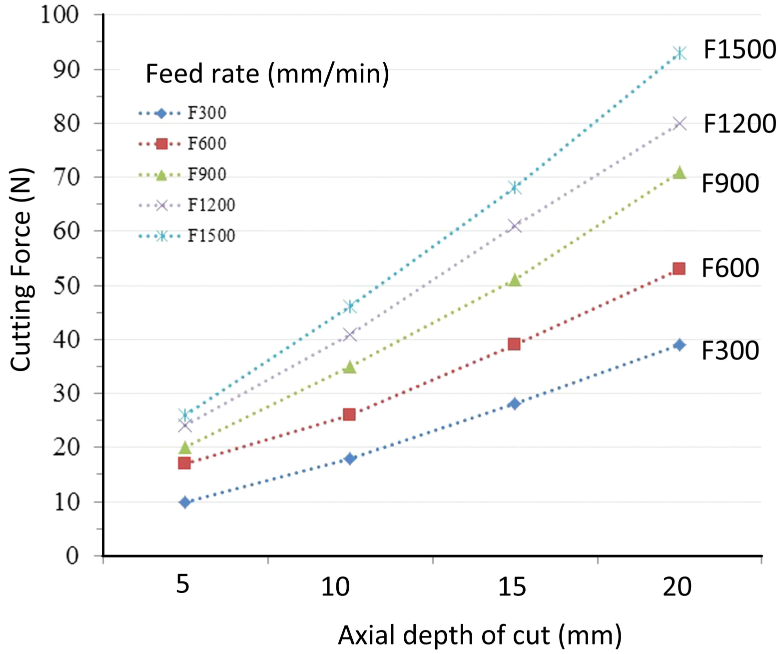

FIGURE 8. The relationship of axial depth of cut, feed rate and cutting force on EVA foam cutting

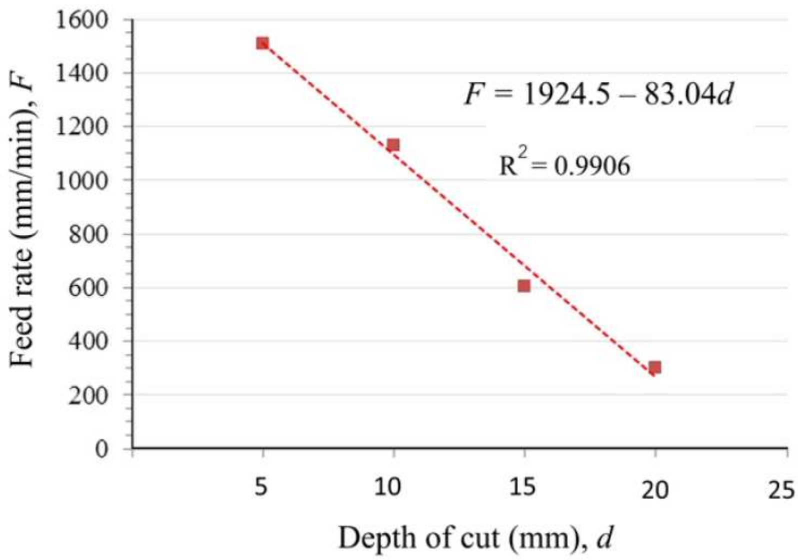

FIGURE 9. The feed rate determination by the axial depth of cut

5. **CMI Manufacturing and Evaluation.** After the optimum cutting parameters were established, they were used for the CMI cutting process at different conditions that can evaluate the quality of the insoles. However, these parameters were obtained from the single spindle cut. When cutting with the multiple independent spindles, it had raised a question, about which spindle feed rate should be referenced. In this research, there were two approaches for assigning the feed rate for multiple spindles. First method is to determine which spindle possesses the deepest depth of cut which would result in the most limited feed rate among all spindles, note that all spindles travel together in the x-y plane. Then the entire operation feed rate is fixed to that specific spindle. This method

is simple and can ensure that no other spindles would cut the material with excessive force as the maximum one is set to limit. On the other hand, at a specific time the depths of cut between all spindles may be varied and therefore the maximum feed rate may be changed among all spindles. To minimize the cutting time, the post-processing software selects the maximum feed rate and switches the referenced spindle depending on the cutting locations. This second method can provide faster cut and called dynamic feed rate method.

In order to evaluate the performance of multiple spindles system in cutting CMI, an experiment was carried out with three cutting methods, a typical single spindle, the multiple spindles with fixed feed, and the multiple spindles with dynamic feed. The experiments conducted based on data from ten diabetic clinical patients in Thailand. For all cases, the first pass of spindles on the workpiece takes the longest time to finish, because most of the area requires the maximum axial depth of cut at 20 mm. Only a portion at the zone, which supports the medial arch, may be required smaller depth of cut. In the second pass, the cut would take the shape of the insole profile and also the outer perimeter. In this step, the cutting times were significantly different. The operating time for all methods was compared and shown in Figure 10. In all cases, the traditional single spindle took about 2-3 times longer to complete in comparison to the multiple spindle system. In average of all cases the single spindle spent about 80.7 minutes to complete one pair of insole. For the multiple spindles system, the average cutting time for fixed feed rate was 32.3 minutes, while the dynamic feed rate was only 28.8 minutes. In percentage, fixed feed rate used about 4.3% longer than the time used in dynamic feed. It is insignificantly different, because both fixed and dynamic feed rate techniques provided almost the same results at the first pass of the cut as almost the entire area required deepest depth of cut. In the second pass, the cutting tool depth will reach most surface area of the insole. At this level, the depths of cut are varied based on the shape of insole profile. The dynamic feed rate technique therefore selects the optimum feed based on this depth variation causing the production rate slightly better than the fixed feed technique.

During the CMI manufacturing, the multiple spindles system had proven to be a great improvement in term of the production rate. It is also necessary to evaluate the accuracy of the cut results. Due to the contour figure of the insole, measuring the shape and size had to be made for the entire surface. To do this, the produced insoles were scanned by

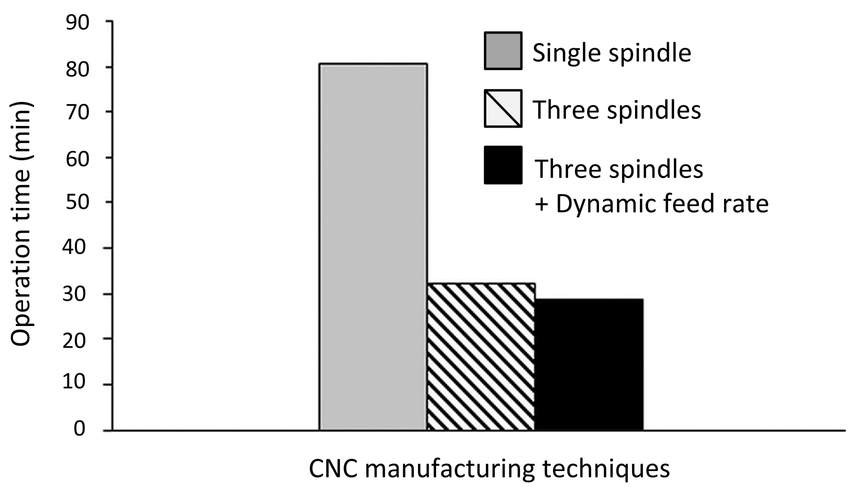

Figure 10. The average of operation time during the CMI manufacturing in three different techniques

the HP 3D Structured Light Scanner Pro S2 which can fabricate the cut insole into 3D model with the accuracy of 0.05 mm. The output 3D models were then compared to the original models used to generate the cutting code. By subtracting an output model from its original, a thin piece of output model with the thickness equivalent to errors produced by the cut can be obtained. To determine the magnitude of errors, all output models were analyzed by the thickness analysis tool in the SolidWorks 2014 program [23]. One or the examples is presented in Figure 11. In this example, the insole was cut using dynamic feed rate with the 40 N cutting force criteria. The results have shown that, the maximum cutting error on the entire insole was 1.2 mm, while the average error was 0.68 mm.

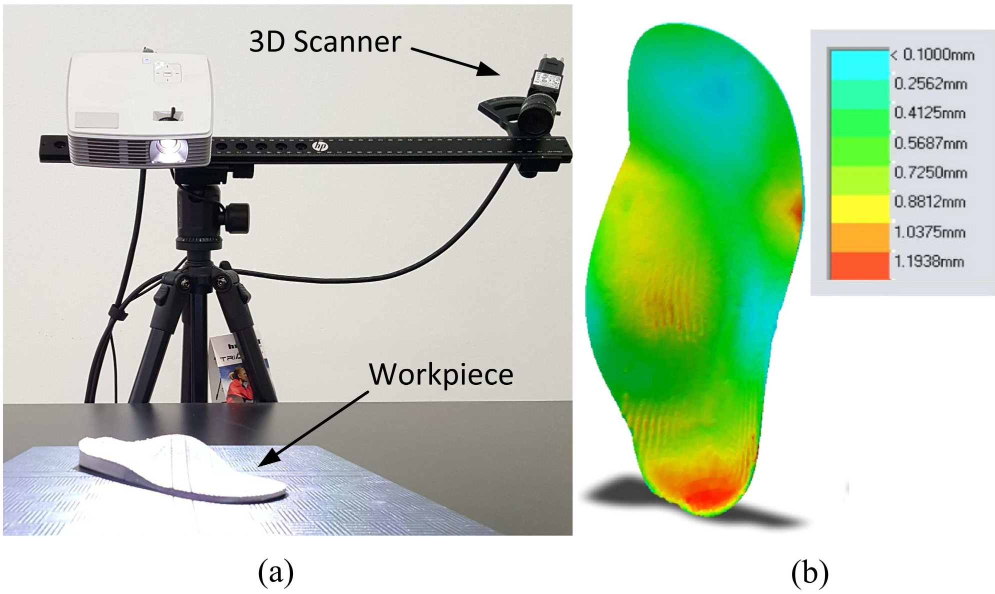

FIGURE 11. (a) The outcome insole was scanned by the 3D scanner. (b) The output model was analyzed by the thickness analysis tool.

In order to evaluate the cut result when using different cutting parameters, the same model was cut in two different conditions. First condition was set to half of the cutting force limit which is 20 N. The result from this condition is shown as case A in Figure 12. The average error was 0.55 mm, while the maximum error was 0.95 mm. When comparing to the optimum 40 N case, shown as case B in Figure 12, it can be seen that the errors from both cases were not significantly different. However, the feed rates of second pass used in case A were about one third of those used in case B. It puts the production time almost twice difference between case A and B. Another cutting condition was set by assigning the feed rate at maximum feed capacity of the machine, 1500 mm/min, without considering the cutting force limit. This condition is marked as case C in the bar chart. The result shows that maximum error has increased up to 3.9 mm, and the average error was also increased to 1.47 mm. While the production time was only improved at about 16%, the error had raised to 216% of the B case. This comparison has verified the optimum cutting parameters obtained in this CMI manufacturing.

6. **Conclusion.** CMI is a practical non-drug treatment for diabetic patients who are suffering from foot ulcer which can lead to the lower extremity amputation. The two major improvements on the CMI manufacturing technique have cut down the production time dramatically, and yet they still maintain the quality of the outcome insoles. The foot sole surface impression machine has been proved to be quick and low cost for capturing the foot sole profiles and converting data to computer models. The captured foot sole profile

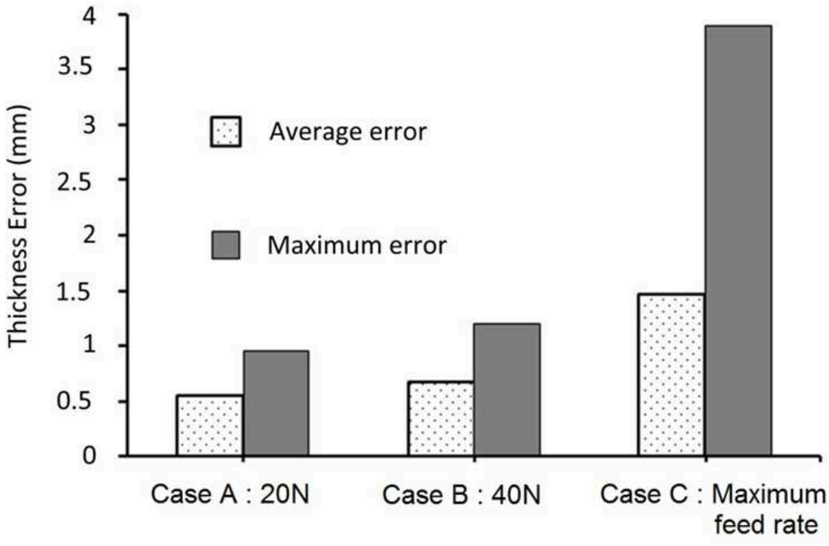

FIGURE 12. The average and maximum error in three different cutting conditions

TABLE 1. The comparison of production time used in the different phases of the conventional method against the enhanced system

Production phase	Conventional method (min)	Proposed system (min)	Improvement (min)
Impression of foot data	5	5	–
Plaster casting model	240	–	−240
CAD model	–	25	+25
Vacuum thermoforming	95	–	−95
Multiple spindles CNC	–	25	+25
Finishing insole	20	20	–
Total time	360	75	−295

was tested for stress distribution performance which is comparable to the traditional impression foam method. Another improvement was made to the CMI cutting process by using the three independent spindles platform. This multiple spindles can share the work load and produce a pair of insole with much faster time. It was feasible by establishing the suitable spindle offset and cutting plan. For cutting EVA foam, the main material used in CMI, the 40 N cutting force limit was used to determine maximum feed rate. This criterion is based on the 6 mm diameter straight flute end mill which is also proven to be the most suitable tool for the CMI cutting in terms of maximum cutting speed and acceptable lay size. In addition, the dynamic feed rate technique for the multiple spindles made a slight improvement of the production time in comparison to the fixed feed, but it was simple to implement.

With all the techniques and the optimum cutting parameters obtained from this research, one pair of CMI can now be made to a patient within 75 minutes in average. When it is compared to the production time used in the conventional method, as shown in Table 1, the enhanced CMI manufacturing system developed in this research can cut down the production time to only 20.8%. In Thailand, between July 2018 and March 2019, this system was put to full operations through several projects. It can produce up to 1,235 pairs of CMI for diabetic patients. It is hoped that this work could be a guideline in development of a low cost CNC platform for fast CMI manufacturing system, and perhaps for some other custom made manufacturing systems using the CAD/CAM technology.

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