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Design and Development of Orthoptic Footwear for Individuals with Flat Feet

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***Abstract* - Flat foot, is a medical condition characterized by a flatter-than-normal medial longitudinal arch (MLA), causing the entire sole of the foot to make close or direct contact with the ground surface. Studies indicate a prevalence of flat foot in the adult population ranging from 13.6% to 26.62%, resulting in foot pain and a diminished quality of life. Orthotic shoes present one treatment method for flat feet. This research aims to analyze the correlation between the arch index and the rear angle of the foot in individuals with flat feet, as well as to design orthotic shoes and insoles. The methodology involved 5 female students with an arch index greater than 0.26, measured through digital sole prints, and the rear angle of the foot assessed using a goniometer. Insole molding design utilized Rhinoceros software and was 3D printed. The insoles were crafted from materials comprising 90% silicone rubber, 10% talc, and 4% hardener of the total. The results indicated that all subjects exhibited flat feet, as evidenced by a non-significant reduction in the eversion angle at the rear corner of the foot. In conclusion, there exists a correlation between the arch index and eversion angle in flat foot measurements. Additionally, orthotic shoes and insoles can be customized based on 3D scanning results, offering effective treatment and comfort for individuals with flat feet.**

Keywords: arch index; eversion angle; flat foot; orthotic insole; orthotic shoes.

I. INTRODUCTION

Flat foot, or fallen arches, is a medical condition characterized by a lower-than-normal medial longitudinal arch (MLA), causing the entire sole of the foot to be in close or direct contact with the ground [1]. Individuals with flat foot, or pes planus, experience a reduction in the arch of the foot, which may lead to discomfort, foot pain, and even postural problems.

Risk factors for flat foot include family history, obesity, age, body mass index, foot length, ligament laxity, diabetes, rheumatoid arthritis, and foot or ankle injuries [2]. Flat foot can increase the workload on foot structures, thereby impairing normal foot function [3]. In addition, flat foot is associated with a higher risk of foot pain, foot injuries, stress fractures, knee pain, and reduced performance in sports activities [4]. The prevalence of flat foot remains unclear due to the lack of standardized radiological criteria for diagnosis. The flat foot condition can occur across various age groups, including children, adolescents, and adults. One study reported that the prevalence of flat foot among adults ranges from 13.6% to 26.62% [5].

One of the treatments for individuals with flat feet is the use of arch supports or foot inserts. This can be achieved by modifying footwear with orthotic insoles. Research studies have shown that three months of orthotic insole treatment in adults can have a positive impact by improving the arch height in flat foot cases [6].Flat foot is generally classified into two types: flexible flat foot and rigid flat foot. The main distinction between these types lies in their underlying conditions-rigid flat foot is often associated with pathological issues requiring special medical attention, whereas flexible flat foot is typically non-pathological. Furthermore, the difference in arch visibility is also notable: in flexible flat foot, the arch appears when the individual is seated, while in rigid flat foot, the arch remains absent even in a seated position.

To address the issue of flat foot, further research involving interdisciplinary collaboration and the development of more advanced technologies is necessary. These efforts are expected to improve the quality of life for individuals with flat foot and reduce the negative impact caused by this condition. This final project aims to design and develop a product intended for individuals with flat foot, specifically to help alleviate pain experienced during walking. The proposed product is an orthotic insole shoe designed to support the arch structure in flat foot cases. The final outcome of this project is a prototype of an orthotic shoe that can be used by flat foot patients in their daily activities.

II. METHOD

This study involved students from the Department of Mechanical Engineering (DTM) at Diponegoro University (UNDIP), aged between 18 and 23 years, with a shoe size greater than 39 (EURO) as the research subjects. In this phase,

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willing participants were asked to undergo 2D foot scanning under loaded (footprint scanning) and unloaded conditions, as well as 3D foot scanning. The footprint scanning was conducted to determine the 2D foot type using a digital footprint scanner, with the output being the Arch Index (AI). Since the focus of this study was to evaluate flat foot, an exclusion criterion was applied: subjects with an AI value of less than 0.26 (indicating high arch or normal arch) were excluded from the study. In addition to foot scanning, participants' body weight and height were measured to calculate the Body Mass Index (BMI).

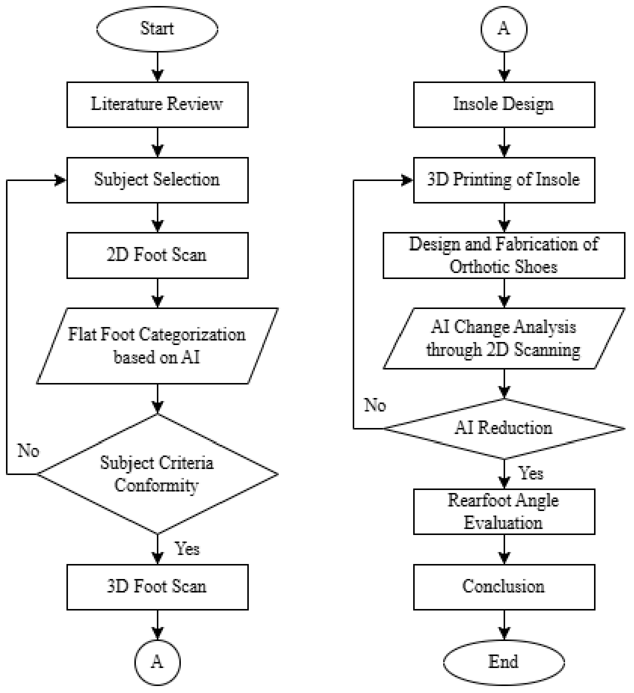

Figure 1: Flowchart of the Research Process

One method of identifying flat foot is through footprint scanning, which includes several techniques. Prior to foot type identification, it is important to understand the division of foot regions. In general, there are two commonly used methods: the Cavanagh method [7] and the Lee Yung-Hui method [8], both of which utilize foot length as the basis for their approach.

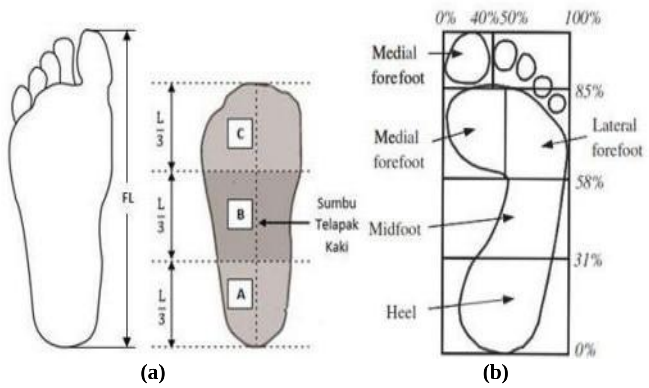

Figure 2: The division of the foot area: (a) Cavanagh and (b) Lee Yung-Hui

One of the methods used in footprint scanning is the Cavanagh Arch Index (AI) method [7]. This method identifies foot type by calculating the arch index, which is the ratio of the midfoot area to the total footprint area excluding the toes, defined as: AI = B / (A + B + C) [7]. In this study, flat foot identification was performed using a custom-built digital footprint scanner, which has been granted a simple patent under the name Gunawan D.H. et al. [9]. The device is based on an A4-sized flatbed document scanner integrated with specialized software [10]. Additionally, this study utilized a 3D scanner to capture three-dimensional foot models. This tool enables flat foot identification using the arch index, where an AI value greater than or equal to 0.26 (AI $\geq$ 0.26) indicates the presence of flat foot [11].

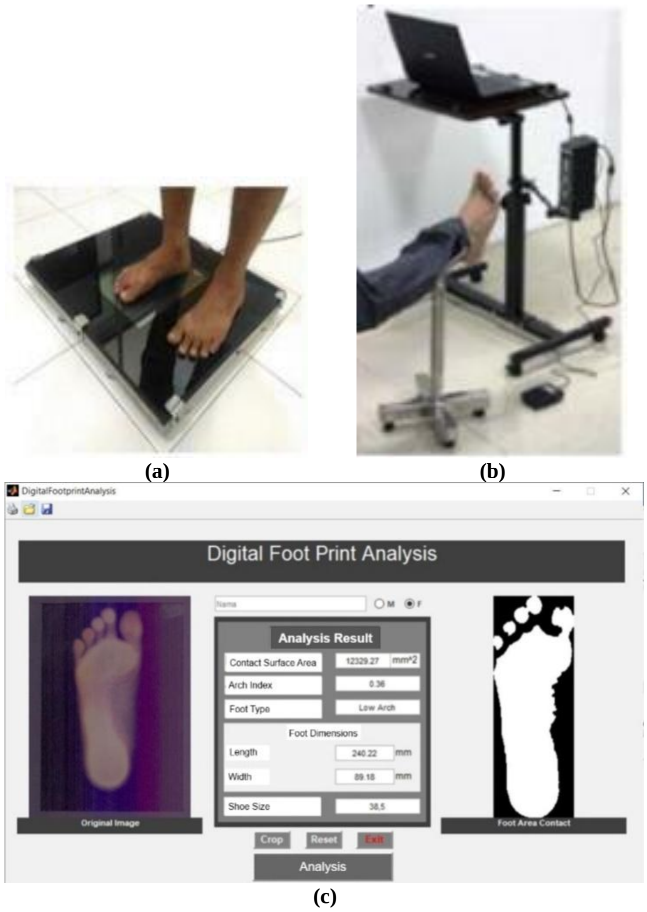

Figure 3: Foot Arch Scanning with (a) Digital Footprint Scanning, (b) 3D Scanner, (c) Digital Foot Print Analysis Application

Flat foot identification in this study also involved measuring the rear foot angle (RFA) using a goniometer. Previous studies have suggested that an RFA value of ≥5°, measured with a goniometer, indicates a flat foot type. In contrast, an RFA value of 4° suggests that the foot is normal [12]. A study on the relationship between Arch Index (AI) and

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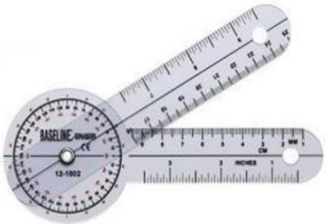
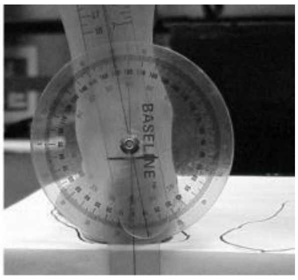
Rear Foot Angle (RFA) showed a significant correlation between these two variables, with an R^2 coefficient of 0.63 for the left foot and 0.73 for the right foot. This relationship led to the formulation of an RFA measurement equation used as a reference for flat foot diagnosis, as shown in Equation 1 for the left foot and Equation 2 for the right foot [13].

$$RFA=46{,}04AI-6{,}41 \quad (1)$$

$$RFA=45{,}37AI-6{,}26 \quad (2)$$



(a)



(b)

Figure 4: (a) Goniometer (b) Measurement of Rear Foot Angle using Goniometer

The next step after the foot scanning process is the identification of the foot coordinates using MATLAB software. This stage aims to obtain the XYZ coordinates from the results of the 3D foot scanning. Below are the results of the foot coordinate identification for Subject 1, presented as a polynomial equation.

Table 1: Sample of Polynomial Equation from Curve Fitting Results

Polynomial Equation	Goodness of fit
$f(x,y)=123.9-0.3038x+0.4152y-0.009553x^2+0.00323xy-0.001685y^2+0.0002525x^3+4.047e\text{-}05x^2y+0.0001055xy^2-7.364e\text{-}05y^3-1.407e\text{-}06x^4-4.971e\text{-}07x^3y+4.869e\text{-}07x^2y^2-4.56e\text{-}07xy^3-7.204e\text{-}10y^4-3.449e\text{-}08x^5+3.792e\text{-}09x^4y-2.148e\text{-}08x^3y^2+6.04e\text{-}09x^2y^3-5.706e\text{-}09xy^4+4.24e\text{-}09y^5$	*SSE:* 1.2168e+04 *R-square:*0.9826

Based on the results of the curve fitting with the fifth-order polynomial equation above, the R-square value obtained is 0.9826, or 98.26%. This indicates the significant combination of variables, or the XYZ coordinates. Since the R-squared value exceeds 0.8, the results of the scan are considered valid for proceeding to the design phase. The foot scanning results can be used as a reference for creating the insole moulding. The moulding insole design process using Rhinoceros software is divided into two parts: the top and bottom surfaces, which are adjusted to the foot anatomy and contours of each subject, in accordance with the area division based on the Cavanagh method. The completed moulding insole design is then 3D printed using PLA filament.

Figure 5: 3D Printing Results of Moulding Insole

The next step is the creation of the insole, using a mixture of three materials: 90% silicone rubber, 10% talc, and 4% hardener of the total mixture. Once the insole is formed, the next phase involves the production of the shoe. The shoe manufacturing process is carried out in collaboration with a shoemaker and consists of four stages: the creation of the shoe pattern, adhering the pattern to hard paper, and gluing the shoe to the outsole. The shoe manufacturing process takes approximately 3 days to complete.

Figure 6: Final Results of Shoe Production

III. RESULTS AND DISCUSSIONS

In this study, body weight and height were measured using a BMI measuring device to classify subjects as underweight, normal, or overweight. The results from 5 subjects showed an average body weight of 55.8 kg, a height of 160 cm, and a BMI of 21.8 kg/m². The purpose of measuring BMI was to identify its relationship with the Arch Index (AI). Table 4.1 presents the evaluation results of the AI for the 5 research subjects, all of whom are students from the Department of Mechanical Engineering, Diponegoro University. Foot scanning was alternated between the left and right feet. This was due to the availability of only one scanning device in the CNC Laboratory, meaning both loaded and unloaded 2D scans were performed alternately. The

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average AI values obtained from the foot scans for the right and left feet were 0.35 and 0.36, respectively.

Table 2: Measurement Results of Body Weight, Height, BMI, and AI

No.	Age (Years)	Body Weight (Kg)	Body Height (cm)
1	20	49	150
2	20	45	167
3	20	80	161
4	20	56	160
5	20	49	160

No.	BMI (kg/m^2)	AI		Average AI
		Right	Left	
1	21,8	0,36	0,33	0,345
2	16,1	0,37	0,41	0,39
3	30,9	0,35	0,34	0,345
4	21,9	0,34	0,35	0,345
5	19,1	0,34	0,39	0,365

The primary reference in designing the insole for flat foot treatment is the parameters derived from various measurement methods. These parameters are obtained through 3D foot scanning and the measurement of the rear foot angle as part of the design evaluation process. The 3D foot scanning was conducted using Vismach scanning technology from China. Among the subjects experiencing flat foot, this final project found no significant correlation between Body Mass Index (BMI) and the 2D Footprint Area (AI). The recorded regression coefficient was only r = 0.2. These results highlight that, although subjects may have underweight (BMI < 18.4 kg/m^2), normal weight (BMI between 18.5 - 22.9 kg/m^2), or overweight (BMI > 23.0 kg/m^2) according to the World Health Organization classification (2010), these factors do not impact the AI value.

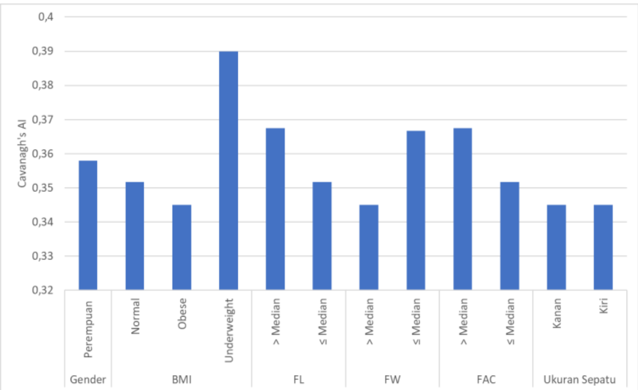

Figure 7: Correlation Graph between AI and Subject Characteristics

Rhinoceros software and the results of the 3D foot scanning were used as tools to assist in designing the insole for the supporting contour in the medial area. Additionally, with this assistance, the design was linked to other parameters measured in this study, allowing for the creation of the insole insert contour design specifically for the medial area.

Figure 8: Shoe Design Results

Figure 9: Insole Design Results

The evaluation of the rear foot angle (RFA) for the subjects was carried out using a manual goniometer with an accuracy of 1°. The measurement process was performed while the subjects stood casually on a flat surface, both with and without the use of the supporting contour. The results of the rear foot angle measurements can be seen in Table 2, where initial EA represents the RFA value before using the insole, and final EA represents the RFA value after using the insole.

Table 3: Evaluation of Rear Foot Angle

No.	Initial EA		Final EA	
	Right	Left	Right	Left
1.	9°	8°	8°	8°
2.	10°	11°	9°	10°
3.	10°	9°	10°	9°
4.	8°	9°	7°	8°
5.	9°	11°	8°	11°

The evaluation demonstrates the effectiveness of using the supporting contour in reducing the eversion angle (EA), as observed in subject 1 and subject 5, where there was a 1° decrease in the right foot. Meanwhile, subject 2 and subject 4 experienced a 1° decrease in EA on both the right and left feet. However, subject 3 showed no reduction in EA values on either the right or left foot. The anatomical-based design approach and the 3D foot contour scanning support the effectiveness of using the supporting contour.

Based on the data obtained, an analysis of the relationship between AI and EA was conducted using Microsoft Excel software. The results show a correlation coefficient (R^2) of 0.41 for the right foot and 0.93 for the left foot, indicating a relationship between AI and EA. From the findings, the minimum EA value was 8° with an AI of 0.34 for

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the right foot, while for the left foot, the minimum EA value was 8° with an AI of 0.33. The following graph shows the correlation analysis results between EA and AI.

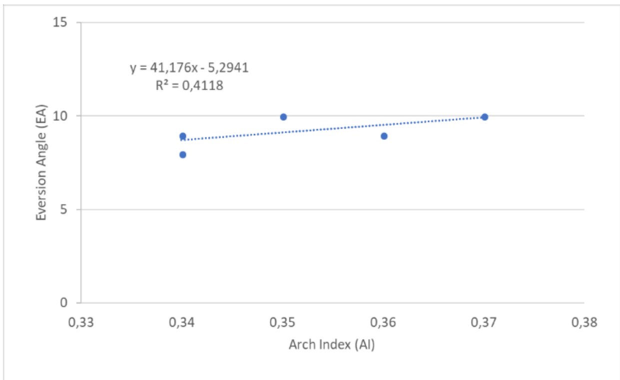

Figure 10: The Correlation Graph of EA and AI for the Right Leg

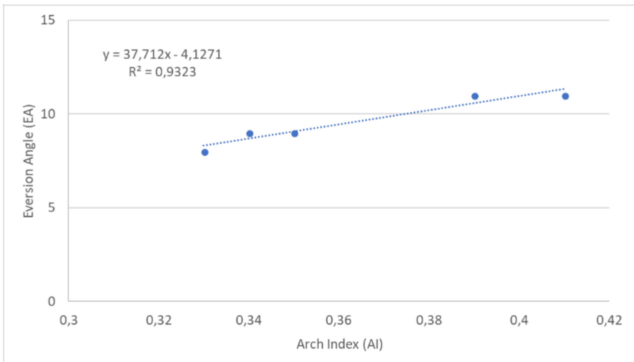

Figure 11: The Correlation Graph of EA and AI for the Left Leg

IV. CONCLUSION

This study contributes to the understanding of the design and development of orthotic shoes for flat foot sufferers and allows for several conclusions to be drawn. The observed correlation between arch index (AI) and eversion angle (EA) can be seen through the measurements taken under flat foot conditions. This comparison indicates that the higher the arch index on a person's foot, the greater the eversion angle they exhibit. Moreover, the medial area design for the support contour follows the 3D foot scanning results of the subject's foot. The support contour was produced using 3D printing technology, resulting in two pairs of insoles. The application of the support contours (shoe-insole) as a strategy for managing flat foot can provide comfort and reduce pain.

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