Development of Footprint Analysis Software Using the Cavanagh Arch Index Method Based on a MATLAB GUI

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Abstract

The human foot plays a crucial role in supporting body weight and maintaining mobility. It is divided into three main sections: the heel, the arch (middle section), and the forefoot. Based on arch structure, feet are categorized into three types: normal, flat foot, and high arch. Flat feet can negatively affect foot health, making the identification of foot types critical for preventive care. In Indonesia, identification often relies on the wet foot test, which has limitations in accuracy. Therefore, a more effective identification system is needed. Previous studies developed software to identify foot types through digital images, but these lacked advanced features and image quality options. This research aims to develop new software that can operate a scanner, process images directly, and offer flexible editing options for improved image quality. The software was developed using MATLAB r2021B GUI, employing image acquisition and processing toolboxes. The results demonstrate high accuracy, with processing differences of 0.73% for length, 1.22% for width, 1.06% for shoe size, 1.34% for FAC, and 2.49% for the arch index compared to previous software versions.

Keywords: Footprint Analysis; Cavanagh Arch Index; MATLAB GUI; Image Processing; Foot Type Identification

Abstrak

Telapak kaki manusia adalah bagian tubuh yang sangat penting, langsung bersentuhan dengan landasan dan menopang seluruh berat badan. Telapak kaki dibagi menjadi tiga bagian utama: tumit, bagian tengah (lengkungan), dan bagian depan. Berdasarkan lengkungan, telapak kaki dibedakan menjadi tiga jenis: normal foot, flat foot, dan high arch. Flat foot sering kali berdampak buruk pada kesehatan kaki, sehingga penting untuk mengidentifikasi jenis telapak kaki guna tindakan pencegahan. Di Indonesia, identifikasi sering menggunakan sistem wet foot test yang kurang efektif. Oleh karena itu, diperlukan sistem identifikasi yang lebih efisien dan cepat. Penelitian sebelumnya telah mengembangkan perangkat lunak untuk mengidentifikasi jenis telapak kaki melalui gambar digital, tetapi memiliki keterbatasan fitur dan kualitas gambar yang rendah. Penelitian ini bertujuan mengembangkan perangkat lunak baru yang dapat menjalankan scanner dan langsung mengolah hasilnya dengan berbagai pilihan kualitas gambar, serta dilengkapi dengan fitur edit yang fleksibel. Perangkat lunak ini dikembangkan menggunakan GUI MATLAB R2021B dengan memanfaatkan toolbox image acquisition dan image processing. Hasil penelitian menunjukkan akurasi yang tinggi, dengan perbedaan hasil pengolahan dibandingkan perangkat lunak sebelumnya sebesar 0,73% untuk panjang, 1,22% untuk lebar, 1,06% untuk ukuran sepatu, 1,34% untuk FAC, dan 2,49% untuk indeks lengkungan.

Kata kunci*: arch, flat foot, MATLAB, Telapak Kaki*

1. Introduction

The human foot plays a crucial role in maintaining daily movement and stability, acting as a vital support structure for the body [1]. The foot and ankle consist of a complex structure, comprising 26 bones, 33 joints (20 actively used), and over 100 muscles, tendons, and ligaments that collectively ensure balance and mobility [2,3]. These elements coordinate to support the foot's arch, enabling effective movement [4].

The size and shape of a person’s foot vary according to factors such as gender, age, height, weight, and daily activities [5,6,7,8]. The sole of the foot is divided into three main sections: the heel, the arch, and the forefoot, which includes the toes [9]. The arch is particularly important for the foot's structure, and its proper development is crucial to avoid deformities or injuries that can impact posture and balance [2].

One common method for determining foot arch type involves measuring the height of the medial longitudinal arch relative to the ground. A distance that is either too large or too small can indicate whether the arch is high or low, and a particularly low distance may suggest flat feet [8,10]. Another widely used method is the Arch Index (AI), developed by Cavanagh, which calculates the area of the rearfoot, midfoot, and forefoot from a standing footprint. An AI value below 0.21 suggests a high arch, between 0.21 and 0.26 indicates a normal arch, and a value above 0.26 suggests a flat foot [10].

Different foot arch types—normal, high, or flat—have various effects on the body. A flat foot, in particular, can lead to issues such as fatigue and heel pain [11]. Approximately 26.63% of adults worldwide have a flat foot condition [5], In Indonesia, however, this condition is often underreported, as many individuals do not experience significant discomfort during daily activities [12]. Nevertheless, an untreated flat foot can adversely affect quality of life, leading to heel pain, foot deformities, and fatigue [12]. In Indonesia, the wet foot test is commonly used to assess foot arch types, although its results can be inaccurate due to technical limitations during the printing process [13].

This study focuses on developing software to analyze foot arch types, building on the work of Varian Adisuryo. The previous software was limited to using a single scanner, with added drivers and features to measure foot length, width, FAC, shoe size, foot type, arch index, and edit features. The goal of this research is to enhance the software by developing a MATLAB-based GUI that utilizes scans from a modified paper scanner, designed to support human weight and offer greater flexibility. In addition to the earlier features, this improved software incorporates direct image acquisition, adjustable threshold settings for enhanced image quality, DPI options for more precise processing, and detailed arch index calculations for each foot area, supporting the calculation of the Arch Index (AI).

2. Materials and Methods

2.1 Research Flowchart

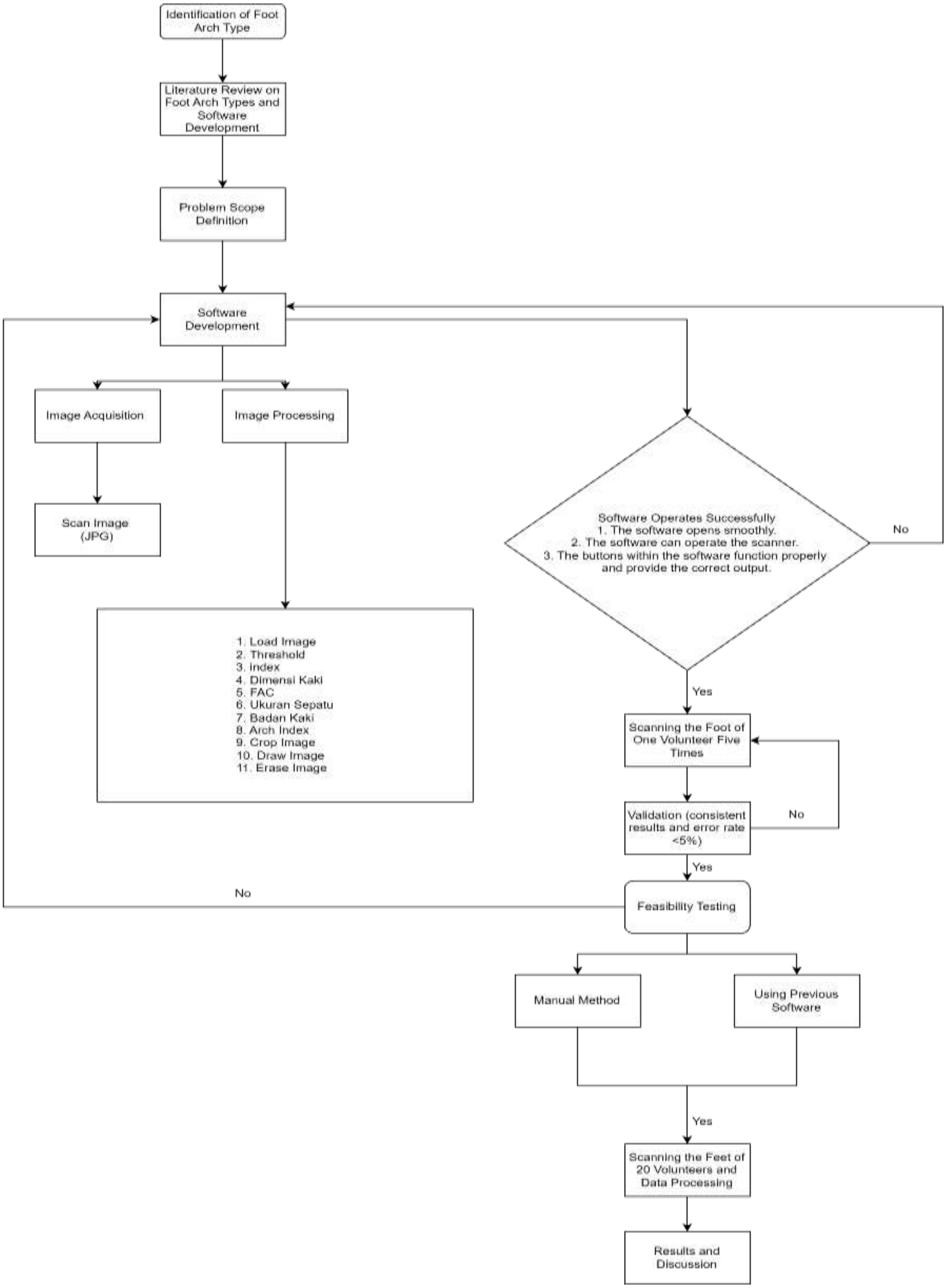

Figure 2.1 Research Flowchart

2.2 Research Location and Duration

This research was conducted in the Mechanical Engineering Department of Diponegoro University, starting in March 2024. The study began with a literature review, followed by the feasibility testing of the results processed by the software developed by the researcher.

2.3 Research Subjects

The subjects of this study were active students of Diponegoro University, aged 20–22 years, consisting of both male and female participants, with a total of 20 individuals.

2.4 Research Methods

To achieve the objectives of this research, the researcher employed an experimental research method. This method was used to test the software's processing of human foot data through five trials using the same subjects. The results were analyzed to determine whether the software consistently produced the same values or varied. The recommended error tolerance threshold is set at below 5%.

2.5 Software Development

The development of this software was carried out using MATLAB R2021b, utilizing the GUI feature offered by MATLAB. By leveraging the available components and MATLAB's provided toolboxes, the software created by the researcher includes adequate features. The toolboxes used include the Image Acquisition and Image Processing Toolboxes. These toolboxes assist users in acquiring images (Image Acquisition) and processing images (Image Processing) more efficiently and easily. The following is **Figure 2.2**, showing the interface of the software developed by the author.

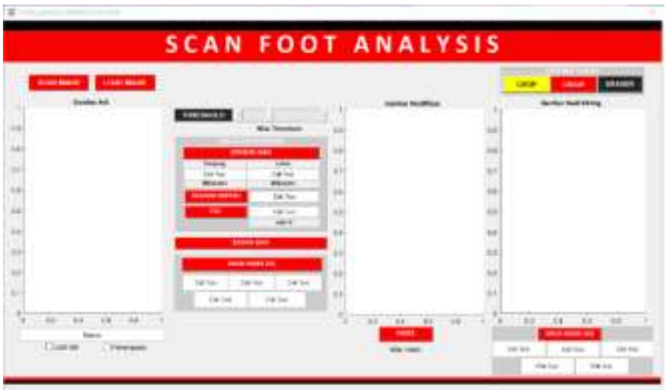

Figure 2.2 Interface of the Developed Software

2.5.1 Footprint Acquisition Process

The footprints of the research subjects were captured using a modified Canon CanoScan Lide 120 paper scanner. The scanner was operated directly through the researcher-developed software, and the scanned results were saved in JPG formatbased .

2.5.2 Image Processing

In image processing to achieve the desired results and values, the researcher used image enhancement, image analysis, and image segmentation techniques. The process of image segmentation to separate the contact and non-contact areas of the foot was performed by (1) converting the RGB image to a grayscale image **(Figure 2.3a)**, (2) selecting the optimal index value for the filter, and (3) converting the grayscale image to a binary image. **Figure 2.3b** shows only the parts of the foot that made contact with the surface.

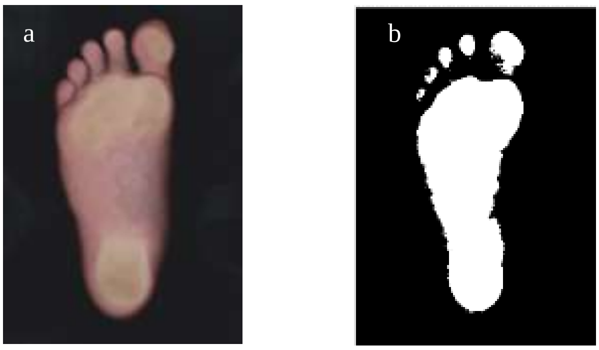

Figure 2.3 (a) Scanned Footprint at 300 DPI Resolution **(b)** Threshold Processing Result with an Index Level of 131

For determining the foot dimensions and the contact area between the foot and the surface, the researcher used equation (1) below.

$$\left(\frac{\textbf{area in pixels}}{\textbf{scanner resolution}}\right) \times \mathbf{645.16\ mm^2} \tag{1}$$

The equation above is used because the images calculated by the software are based on pixel measurements, so they must first be converted into millimeters [14]. Once converted, the values for length, width, and contact area can be calculated using the software.

To determine the arch index and foot type, the researcher applied the Cavanagh Arch Index method. The procedure involved drawing a line from the center of the heel to the tip of the second toe, then extending this line to the edge of the heel. This line is referred to as the heel center line. Next, a perpendicular line was drawn from the second toe's base across the heel center line to exclude the toes and divide the sole (without the toes) into three equal parts, as shown in **Figure 2.4** below [10].

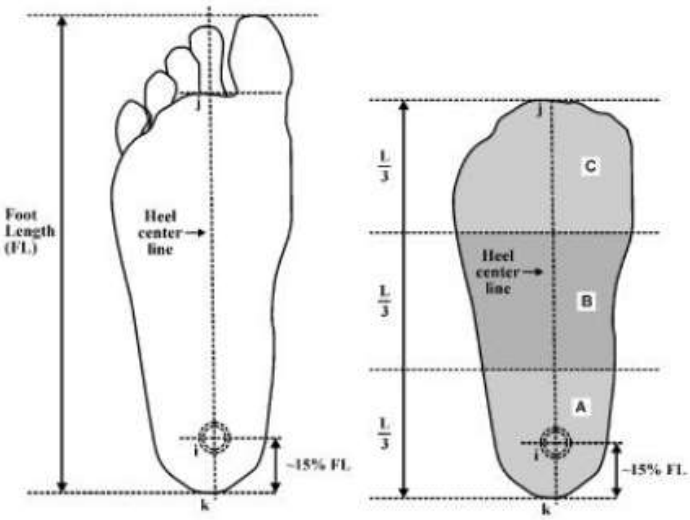

Figure 2.4 Foot Identification Using the Cavanagh Arch Index

This procedure for excluding the toes, as illustrated in Figure 2.4, was entirely performed through the software developed by the researcher using a custom-coded program. The toes were separated from the main foot area by increasing the index value and creating a specific mask for segmentation. Clear illustrations can be seen in **Figures 2.5(a)** and **2.5(b)** below.

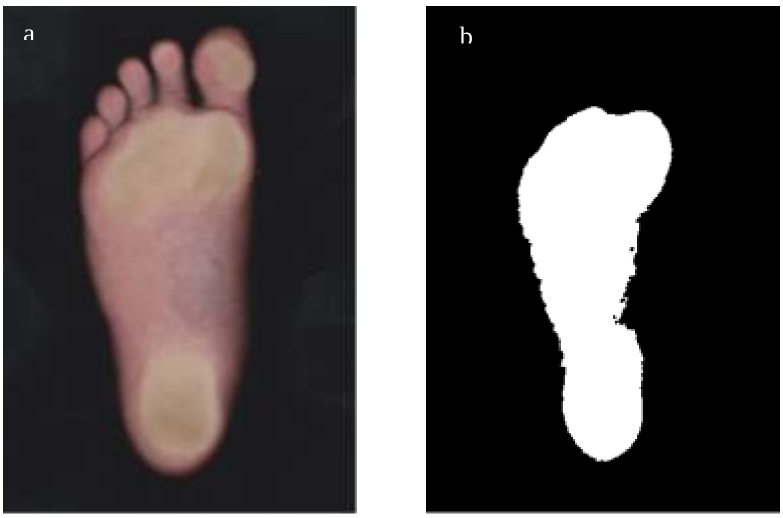

Figure 2.5 (a) Scanned Footprint at 300 DPI Resolution **(b)** Footprint Removal Result

The Arch Index (AI) is then calculated by dividing the area of the middle region (Section B) by the total area of the foot without the toes, as shown in equation (2) below.

$$AI = \frac{B}{(A + B + C)} \tag{2}$$

2.6 Canon CanoScan Lide 120 Scanner

The scanner used in this research was a modified Canon CanoScan Lide 120. The modifications included replacing the original glass with a new 10 mm-thick glass, constructing a new frame capable of supporting up to 100 kg of body weight, and removing the tray cover. The details of the modifications can be seen clearly in **Figures 2.6(a)** and **2.6(b)** below.

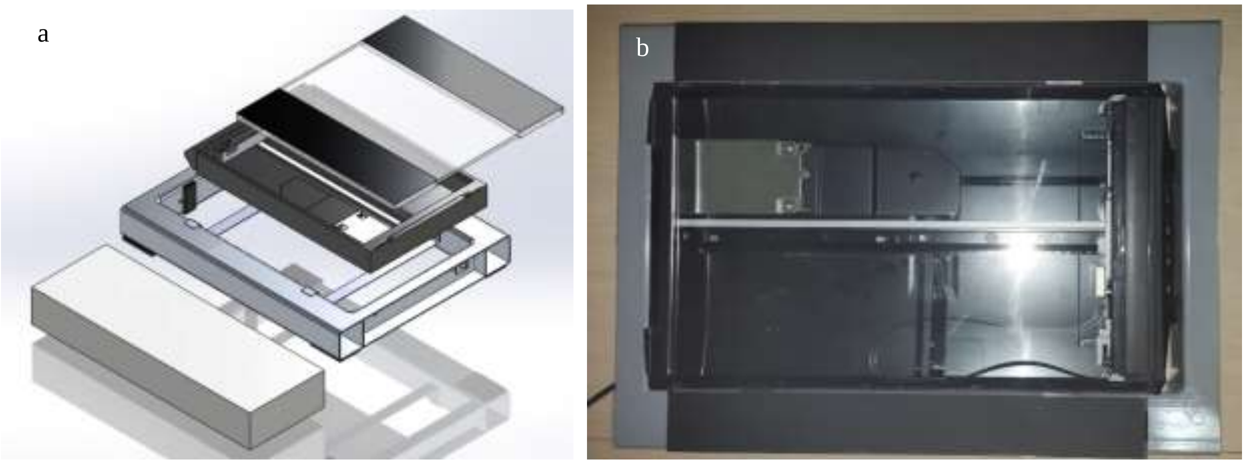

Figure 2.6 (a) Modified Shape **(b)** Modification Result

This foot scanner was designed to scan one foot at a time while the other foot rests on a wooden platform. During the scanning process, the foot is expected to be clean, and the subject is instructed to stand upright on the scanner to obtain an optimal image free from external light interference [15]. Therefore, a black cloth is used to cover the foot and prevent external light from affecting the scan. The foot positioning on the scanner and the black cloth covering can be seen in **Figure 2.7** below.

Figure 2.7 Foot Standing on the Scanner for Scanning Process with a Fabric Cover

3. Results and Discussion

3.1 Consistency Check of Footprint Processing Results with the Scan Foot Analysis Software

To ensure the developed software produced consistent data, a test was conducted to evaluate whether the software generated results with an acceptable error rate. In this study, the footprint of a single subject was captured five times, and the results were analyzed using the developed software. The software is considered suitable for use if the error rate across all five trials remains below 5%. An example of the footprint analysis results is shown in **Figure 3.1** below.

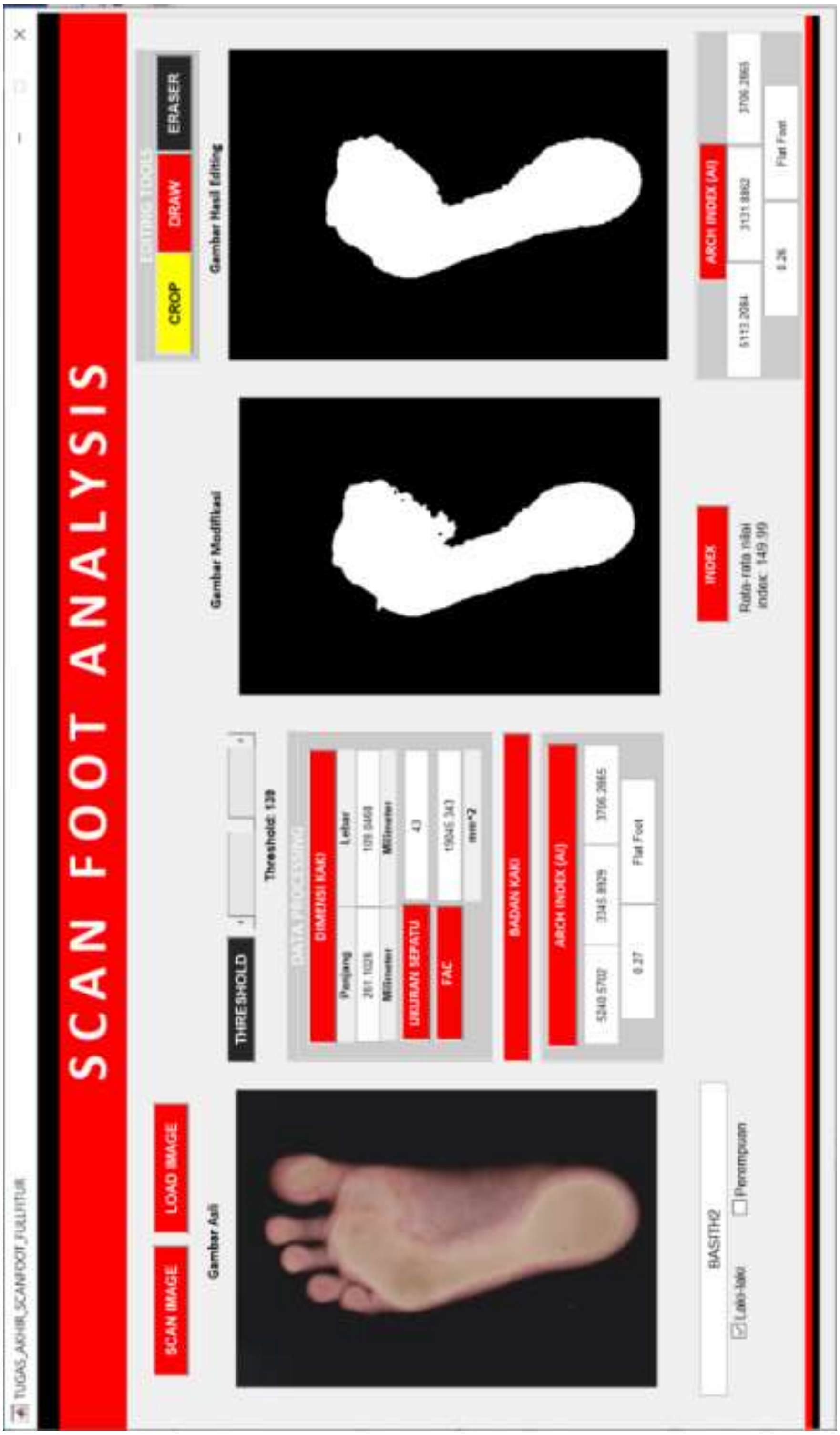

Figure 3.1 Footprint Processing Result Using the Scan Foot Analysis Software

The calculation used to determine the error value is presented in equation 3.1 below.

$$\text{error (\%)} = \left(\frac{\frac{(\text{maximum value} - \text{minimum value})}{2}}{\text{mean}}\right) \text{x } 100 \tag{3.1}$$

The processing results of the five footprints by the Scan Foot Analysis software are displayed in **Tables 3.1** and **3.2** below.

Table 3.1 Processing Results of Research Subjects' Footprints for Foot Dimensions and FAC in Millimeters

NO	INDEX	THRESHOLD	FOOT DIMENSIONS (mm) Length	Width	FAC (mm)	Shoe Size
1	150.65	139	261.95	113.54	19093.94	43
2	149.99	139	261.1	109.05	19045.34	43
3	149.81	139	260.26	109.13	18896.74	43
4	149.51	139	262.12	107.52	19069.51	43
5	150.58	139	261.78	104.64	19122.24	43
mean	150.11	139	261.44	108.78	19045.55	43
error (%)			0.36	4.09	0.59	

For the calculation of the arch index, equation 3.2 was used.

$$AI = \frac{B}{(A + B + C)} \tag{3.2}$$

Table 3.2 Processing Results of Research Subjects' Footprints for Arch Index Values and Their Types

	Initial ARCH INDEX (AI) (mm)				Type of AI	Edited ARCH INDEX (AI) (mm)				Type of AI
	Area A	Area B	Area C	AI		Area A	Area B	Area C	AI	
	5174.46	3312.32	3744.28	0.27	Flat Foot	5072.83	3092.66	3718.11	0.26	Flat Foot
	5240.57	3345.89	3706.28	0.27	Flat Foot	5113.2	3131.89	3706.29	0.26	Flat Foot
	5071.11	3296.32	3618.31	0.28	Flat Foot	4873.72	3081.06	3618.31	0.27	Flat Foot
	5071.57	3355.21	3756.26	0.29	Flat Foot	5036.89	3217.68	3699.38	0.27	Flat Foot
	5089.9	3308.33	3729.91	0.29	Flat Foot	5121.91	3346.87	3636.64	0.28	Flat Foot
mean	5129.522	3323.61	3711.008	0.28		5043.71	3174.03	3675.75	0.27	
error (%)	1.65	0.89	1.86	3.57		1.62	2.15	1.10	3.73	

The results from the Scan Foot Analysis software, based on the processing of five identical footprints, as shown in **Tables 3.1** and **3.2**, demonstrate minimal error rates. **Table 3.1** presents data on the index values and thresholds obtained during image processing. Using a DPI of 300 for each image, the average index value obtained was 150.11. This indicates that the brightness of each image falls within the expected range. The optimal threshold for converting the image to black and white, without distorting the original image, was within a range of 10 units.

Furthermore, the repeated measurements of length and width also showed error rates below 5%, with the length error rate at 0.36% and the width error rate at 4.09%. The average Foot Area Contact (FAC) value obtained from the footprint analysis was 19,045.55 millimeters, with an error rate of 0.59%. For the arch index calculation, the data also provided information on each section of the foot. The error rate for the forefoot (A) was 1.65%, for the midfoot (B) 0.89%, and for the heel (C) 1.86%. The error rates for all three parts of the foot were very low, even below 2%. The average arch index remained stable at 0.29, with an error rate of 3.57%, indicating a flat foot type, as the value exceeded 0.26.

Additionally, some images required refinement, such as cropping and redrawing, to conform to the Cavanagh Arch Index standard, which calculates only the foot body without the toes. The results for areas A, B, and C after editing were 1.62%, 2.15%, and 1.10%, respectively, with an arch index of 0.27 and a repeated error rate of 3.73%, indicating a flat foot type.

Based on the data obtained, the overall results from the Scan Foot Analysis software showed consistent values. The error rates below 5% indicate that the software is reliable for use. While these results reflect consistency, ensuring that the software meets accuracy standards is crucial for its broader application. Therefore, it should be compared with other recognized software available for benchmarking.

3.2 Feasibility Comparison of the Scan Foot Analysis Software with Digital Footprint Analysis

The software, after consistency testing, will now be validated by comparing its results with Adisuryo's Digital Footprint Analysis software, which serves as a reference and benchmark for developing the Scan Foot Analysis software. Adisuryo's software, patented in 2019 under number IDS000002253, was developed using MATLAB r2015a's GUI.

The interface of the Digital Footprint Analysis software features two axes: the left axis displays the original image, while the right axis shows the processed image. The software includes a single command button labeled "Analysis," which generates all output data, including contact area, arch index, foot type, foot dimensions, and shoe size. It also has a "Crop" option that allows users to select a rectangular portion of the image, but it does not alter the image even after selection. A "Reset" feature clears all processed results, and the "Exit" button functions similarly to the close button in the top right corner.

The Digital Footprint Analysis software uses the Cavanagh arch index method to determine foot type, the same method used in the author's developed software. However, the earlier software could only process images and did not support direct image capture or scanner operation. Additionally, it lacked adjustable threshold and DPI settings, making it incompatible with modern scanners, leading to inaccurate image analysis when used with scanners that do not match the software's initial configuration.

To demonstrate the accuracy of the author's software, a comparison was made between the image processing results of the previous software and the newly developed software. Since each software is designed to work with its respective scanner, the footprints were captured using their respective scanners, as shown in Figures 3.2a and 3.2b. This comparison was necessary because the previous software could not process images from modern scanners.

Figure 3.2 (a) Using the Old Scanner **(b)** Using the New Scanner

To compare the results, the author used 20 different footprints from various individuals, each printed using their respective scanners, for processing and comparison. Below are **Figures 3.3** and **3.4**, which show the processed footprints.

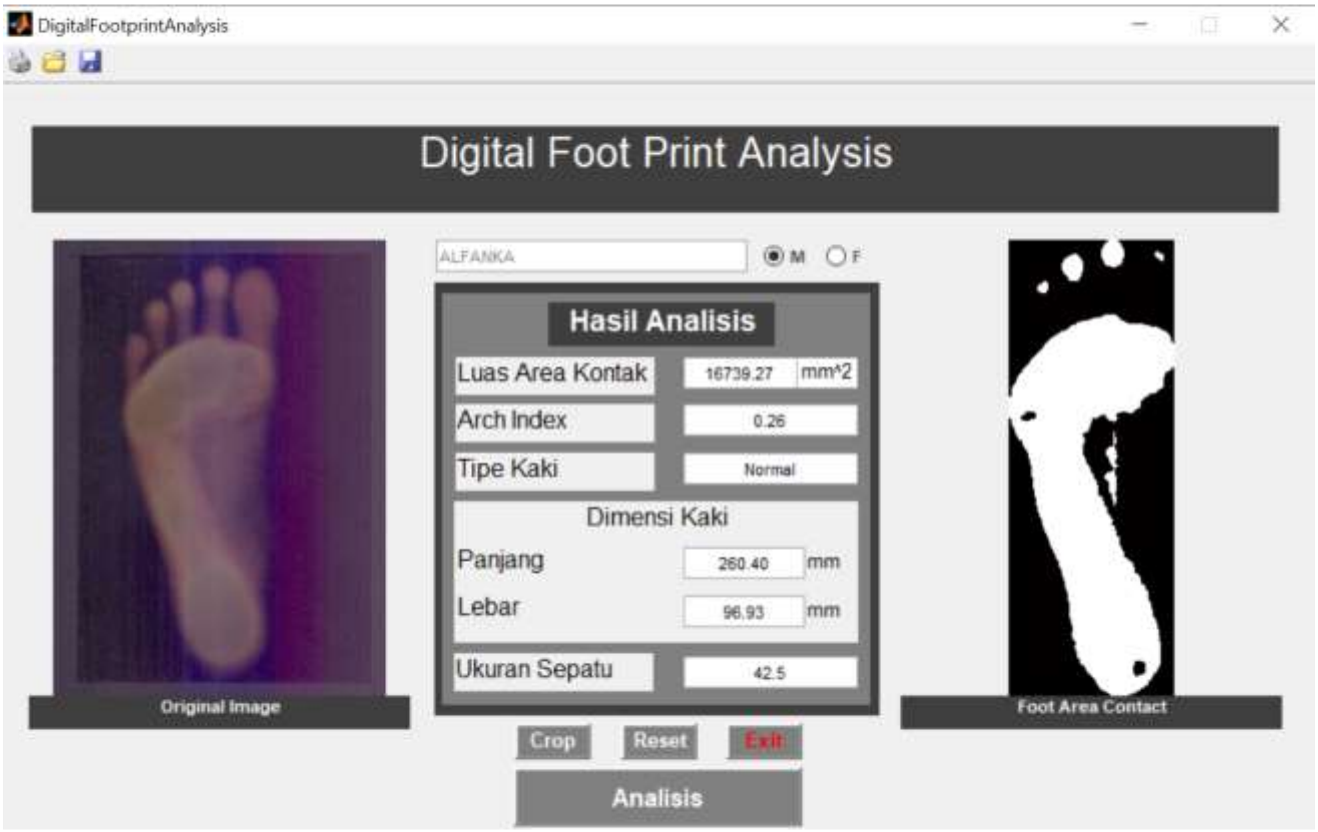

Figure 3.3 Processing Result with the Old Software

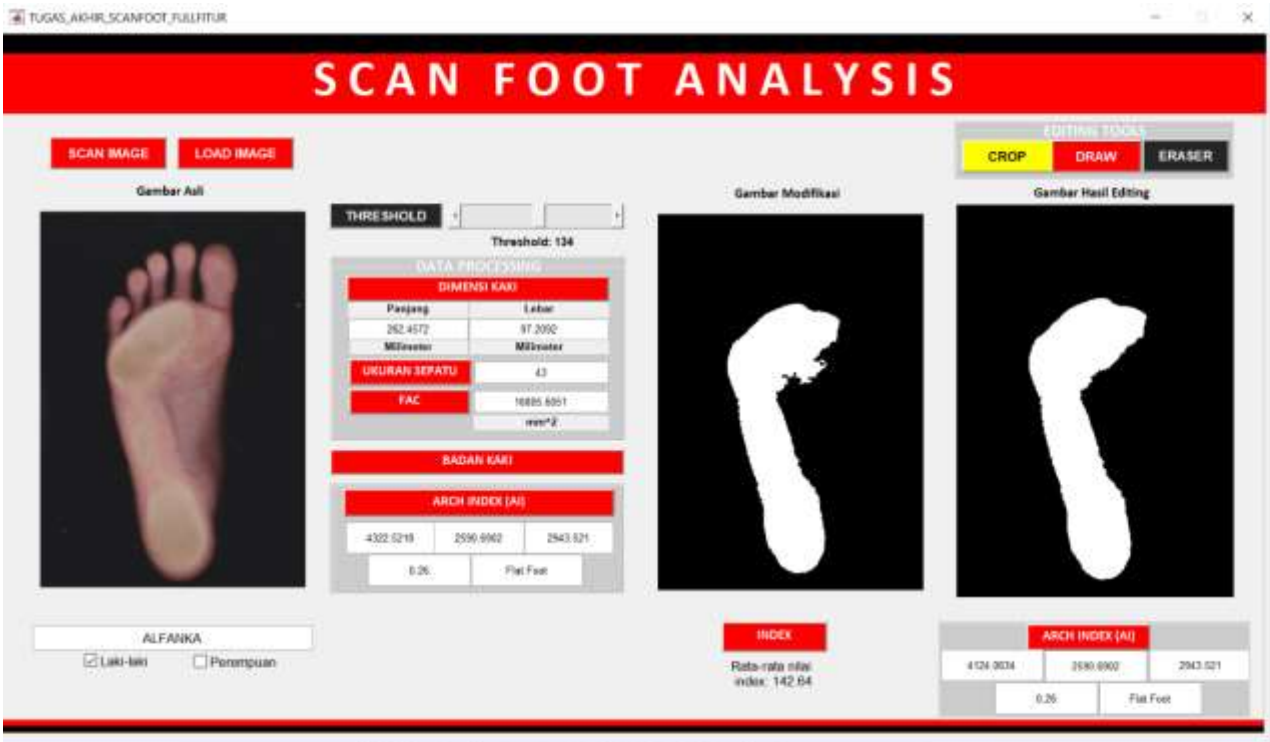

Figure 3.4 Processing Result with the New Software

Other processed data can be seen in the comparison table below,

Table 3.3 Comparison of Data from Digital Footprint Analysis Software and Scan Foot Analysis Software

Subject Name	Foot Dimensions (mm)						Shoe Size			FAC (mm2)			Arch Index			Foot Type		Gender
	Length (previous)	Length (current)	Error (%)	Width (previous)	Width (current)	Error (%)	Previous	Current	Error (%)	Previous	Current	Error (%)	Previous	Current	Galat (%)	Previous	Current	
Subject 1	258,38	259,75	0,53	98,07	97,36	0,73	41,5	42	1,19	18699,1	18362,72	1,83	0,29	0,3	3,33	low arch	flat foot	M
Subject 2	260,4	262,46	0,78	96,93	97,21	0,29	42,5	43	1,16	16739,27	16805,6	0,39	0,26	0,26	0	normal	flat foot	M
Subject 3	268,29	272,87	1,68	96,29	97,87	1,61	44	45	2,22	18746,66	18852,85	0,56	0,29	0,28	3,57	low arch	flat foot	M
Subject 4	248,15	247,15	0,40	89,3	89,49	0,21	39	39	0	15602,51	15171,03	2,84	0,41	0,41	0	low arch	flat foot	F
Subject 5	260,92	261,7	0,30	107,72	104,22	3,36	42	43	2,33	18874,98	19357,06	2,49	0,43	0,42	2,38	low arch	flat foot	M
Subject 6	243,14	245,86	1,11	103,15	101,43	1,70	40	40	0	17660,96	17437,55	1,28	0,4	0,42	4,76	low arch	flat foot	M
Subject 7	259,14	262,95	1,07	113,31	113,53	0,19	42	43	2,33	19098,65	19093,94	0,02	0,28	0,27	3,70	low arch	flat foot	M
Subject 8	237,43	237,1	0,14	88,29	90,76	2,72	37	37	0	14956,06	15225,01	1,77	0,42	0,42	0	low arch	flat foot	F
Subject 9	250,25	251,37	0,45	101,63	104,76	2,99	40,5	41	1,22	18957,2	18717,16	1,28	0,41	0,4	2,5	low arch	flat foot	M
Subject 10	251,74	252,47	0,29	99,59	99,39	0,20	41	41	0	17480,28	17933,38	2,53	0,4	0,39	2,56	low arch	flat foot	M

Subject 11	261	261,19	0,07	106,42	107,44	0,95	42	43	2,33	18788,71	18698,38	0,48	0,28	0,27	3,70	low arch	flat foot	M
Subject 12	257,11	259,32	0,85	109,87	111,16	1,16	41,5	42	1,19	18397,59	18749,8	1,88	0,29	0,27	7,41	low arch	flat foot	M
Subject 13	268	269,99	0,74	115,31	114,97	0,30	44,5	44	1,14	20768,45	20857,29	0,43	0,35	0,34	2,94	low arch	flat foot	M
Subject 14	231,2	231,55	0,15	91,08	91,27	0,21	37	37	0	14728,02	14441,44	1,98	0,35	0,35	0	low arch	flat foot	F
Subject 15	245,17	248,99	1,53	95,27	97,19	1,98	40	40	0	17256,13	17354,49	0,57	0,36	0,36	0	low arch	flat foot	M
Subject 16	255,08	257,8	1,05	94,89	96,6	1,77	41	42	2,38	17224,16	17469,91	1,41	0,34	0,33	3,03	low arch	flat foot	M
Subject 17	255,59	257,63	0,79	106,45	105,41	0,99	41,5	42	1,19	18591,79	18736,55	0,77	0,3	0,29	3,45	low arch	flat foot	M
Subject 18	239,53	240,44	0,38	93,88	93,89	0,02	39	39	0	15326,53	15786,58	2,91	0,39	0,39	0	low arch	flat foot	F
Subject 19	247,33	249,67	0,94	94,13	91,77	2,57	40,5	40	1,25	16913,99	17127,29	1,25	0,35	0,35	2,86	low arch	flat foot	M
Subject 20	246,7	249,93	1,29	98,58	98,12	0,47	40,5	40	1,25	16364,11	16339,28	0,15	0,27	0,28	3,57	low arch	flat foot	M
Mean			**0,727**			**1,22**			**1,06**			**1,34**			**2,49**			

The table above compares the scan results between the *Digital Footprint Analysis* software and the *Scan Foot Analysis* software. Both programs provide outputs such as foot dimensions, Foot Area Contact (FAC), and arch index.

First, in terms of foot dimensions, the comparison shows that the error margins for foot length, width, and shoe size are relatively low. The highest error margin for foot length is 1.67%, with the previous software recording 268.29 mm and the new software recording 272.87 mm. The lowest error margin for foot length is 0.073%, with the previous software showing 261 mm and the new software showing 261.19 mm. The average error rate for foot length scans is 0.73%.

For foot width, the highest error margin is 3.36%, with the previous software recording 107.72 mm and the new software recording 104.22 mm. The lowest error margin is 0.01%, with both programs recording nearly identical values of 93.88 mm and 93.89 mm. The average error rate for width measurements between the two programs is 1.22%.

Regarding shoe size, the comparison shows a highest error margin of 2.38%, with the previous software yielding a size of 41 and the new software yielding 42. The lowest error margin for shoe size is 0%, with both programs recording a shoe size of 40. The average error rate for shoe size measurements is 1.06%.

Next, for Foot Area Contact (FAC), the results show that the highest error margin is 2.91%, with the previous software recording 15,326.53 mm² and the new software recording 15,786.58 mm². The lowest error margin is 0.025%, with the previous software showing 19,098.65 mm² and the new software showing 19,093.94 mm². The average error rate for FAC between the two programs is 1.34%.

Finally, for the Arch Index, the highest error margin is 7.41%, with the previous software recording 0.29 and the new software recording 0.27. The lowest error margin is 0%, with both programs recording an identical value of 0.26. The average error rate for Arch Index measurements is 2.49%.

Several factors can influence these differences in results, such as the condition of the feet during scanning, whether the feet were dirty or dusty, and differences in foot positioning during the scan. Variations in shoe size results are also influenced by the reference system used by each software. For instance, subject 1 had a foot length of 258.38 mm with a shoe size of 41.5 in the previous software, while the new software recorded a length of 259.75 mm and a shoe size of 42, with both programs using a 5 mm range for shoe size transition.

Differences in Arch Index values and foot type classification are influenced by the threshold settings used for image selection, which vary between the two programs, leading to differences in foot body removal and calculation outputs. Moreover, the previous software misclassified foot type according to the Cavanagh method, where a flat foot should have a value of 0.26 or higher. The new software determines the Arch Index automatically, without requiring manual editing.

4. Conclusion

The development of the *Scan Foot Analysis* software to operate the scanner and process the scan results provides conclusions aligned with the research objectives, as follows:

1. The developed software has demonstrated accuracy, as repeated testing of the same footprint yielded an error rate below 5%. Specifically, the length error rate was 0.36%, and the width error rate was 4.09%. The error rate for Foot Area Contact (FAC) was 0.59%. The arch index was calculated for each part of the foot, showing an error rate of 1.65% for the front foot (A), 0.89% for the midfoot (B), and 1.86% for the heel (C). These values were consistently low, all below 2%. The average arch index remained stable at 0.29, with an error rate of 3.57%, indicating a flat foot type as the value exceeded 0.26. In addition to numerical results, adjustments were needed to comply with the Cavanagh Arch Index standard. The images were edited to crop and remove the toes, focusing only on the foot body, followed by recalculations. The recalculated results for A, B, and C were 1.62%, 2.15%, and 1.10%, respectively, with an arch index of 0.27 and a repeated error rate of 3.73%, still indicating a flat foot type.
2. The comparison between the two software programs aimed at validating the results showed relatively low error rates. For length measurement, the highest error rate was 1.67%, and the lowest was 0.073%, with an average error rate of 0.73%. For width measurement, the highest error rate was 3.36%, and the lowest was 0.01%, with an average error rate of 1.22%. For shoe size, the highest error rate was 2.91%, and the lowest was 0.025%, with an average error rate of 1.06%. Some discrepancies in shoe size results were noted, even within the same length range, due to differences in the references used by each software. For FAC, the highest error rate was 2.84%, and the lowest was 0.025%, with an average error rate of 1.34%. Finally, for the arch index, the highest error rate was 7.41%, and the lowest was 0%, with an average error rate of 2.49%. Overall, the comparison demonstrated that both software programs produced low error rates across multiple measurements, validating the accuracy of the developed software.

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