Passive Prosthetic Ankle Design Based on Indonesian Anthropometry

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ABSTRACT

Foot prosthesis is a replacement for the foot to overcome activity limitations due to disease, birth defects, accidents, or amputations. Many foot prosthetics have been developed in recent years to treat patients. However, prostheses on the market today have drawbacks, including their high price, lack of comfort, stiff ankles, and low durability. The main objective of this study is to develop an existing ankle-foot prosthesis design that approximates the resemblance of a human foot according to the anthropometry of Asians, especially Indonesians. This study contains the design of a prosthetic foot with a skin design model and a support core. The prosthetic core supports the use of a compliance mechanism (CM) model that functions to connect the limb organs that have been amputated. The design process is carried out using the Solidwork software. Ankle foot prostheses are designed to be able to withstand a load of 100 kg and can be used for patients with a height range of 150 cm to 180 cm. Based on the design results, it is found that the prosthesis mass is lower than the lowest mass of the user, so it feels light, ergonomic, and flexible when used.

Keywords: *Ankle-foot, anthropometry, compliant mechanism, design*

I. Introduction

Feet are very important lower limbs, where the majority of functional activities of the human body are carried out by the feet, such as walking, exercising, cycling, and praying for a Muslim. However, some circumstances such as trauma, accidents, blockage of blood flow, and the presence of congenital diseases that result in amputation make humans have lower limbs that are not good and healthy. One way to restore normal motion for amputees is to use a prosthesis. One of the most important parts of the foot prosthesis in both below-knee and above-knee amputations is the ankle-foot. Several researchers have designed ankle-foot prostheses, including prostheses with small and thin designs [1], prosthesis with control device and electric drive source [2], and also prosthetics with springs, clutches, and motors [3]. However, these models still have shortcomings, including models that are too complex, difficult to use, heavy, and expensive, so that they are still difficult to reach for people in developing countries such as Indonesia. Departing from these problems, it is still necessary to design a foot prosthesis that is lightweight, easy to use, and inexpensive.

One of the keys to designing a new prosthesis is patient response analysis. This is important because if the design made does not provide functional, practical, and aesthetic characteristics, it will cause discomfort for the patient. The characteristics of the ankle-foot prosthesis that are considered important by patients to support natural activities include

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dorsiflexion, eversion, energy return, impact absorption, and ankle torsion. Lack of understanding of ankle-foot biomechanics and the dynamic interactions between the amputated body and the prosthesis are major obstacles in designing new prostheses that mimic natural function and form.

There are two types of ankle-foot prosthesis that are common in the market, namely passive and active movement types. Passive prosthesis is very affordable for amputee rehabilitation. The type of active prosthesis is currently growing rapidly, but it still requires power to produce energy. Passive prostheses include springs to ensure storage and energy, as well as dampers to suppress vibration. Previous studies have considered an ankle foot prosthesis with a solid ankle-based cushioned heel model [4]. There are several criteria that must be considered in designing a passive type of ankle-foot prosthesis. The first is related to portability capacity, where the priority criteria are the size and lightness of the prosthesis. The second is the design of the prosthesis, which is simple and affordable.

Some researchers make and develop passive ankle-foot designs to get the prosthesis function in accordance with the normal human body. Pham et al. [5] made an ankle-foot design with type of multi-axis fully compliant prosthetic ankle (MAPCA) and its biomechanical behavior using the finite element method. As a result, the design characteristics are more flexible and can reduce impact forces on the residual limbs. Koehler-McNicholas et al.[6]compared the performance of passive, hydraulic and non-hydraulic ankle-foot prosthesis in minimizing individual socket reaction moments with transtibial amputation during sideways walking activities. Dao & Le Chau [7] analyzed the design of a passive prosthetic ankle-foot made of glass fiber reinforced plastic with biomechanics, simulation, and optimization.

In this study, a compliant mechanism (CM) is used or also known as a flexibility-based mechanism. This type of CM has friction-free, no backlash, and monolithic fabrication, which is a special kind of mechanical engineering [8]. Therefore CM has lightweight. The study of compliant mechanisms is new research on design. But it has potential in use because of its advantages when compared to rigid-body mechanisms. One of the advantages is in its durability, which has flexible properties that can return to its original position after being moved or released. In addition, it is lighter but stronger and cheaper.

Some researchers are also considering the ankle-foot design using a suitable mechanism. Miller & Childress [9] investigated the influence of vertical compliance prosthetic foot for various activities when used by persons with amputation. Scholarsarchive & Wiersdorf [10] develop design approaches and models for prosthetic ankle joints using kinematic models of the human ankle and compliant mechanism technology. Maykranz & Seyfart [11] developed the spring-loaded inverted pendulum (SLIP) model by extending with a foot segment and a compliant ankle joint. The purpose is to extend foot contact and the displacement of the center of pressure during contact.

This research is to design an ankle-foot prosthesis by combining currently available prosthetic design elements to be developed into a new prosthesis. The newly designed ankle-foot prosthesis will exhibit a wider range of properties and characteristics than existing ones. Thus, the new ankle-foot prosthesis will better represent the functionally normal human foot. The development of the ankle-foot prosthesis design in this study is a model that is adapted to the anthropometry of Asian people, especially Indonesians who have a height between 150 cm to 180 cm. The design consists of an outer shell and a support core. This prosthesis is expected to be able to replace the function of the ankle-foot as it should by paying attention to anthropometric aspects.

II. Material and Methods

The prosthesis design is a process that starts from the discovery of the need for the prosthesis until the final design for the manufacture of a prototype. The process of making the ankle-foot design in this study begins with observing the prosthesis products on the market. Observations were made to obtain information about the advantages and disadvantages of the product so that further product development can be carried out. The need for repair of the prosthesis product that is needed based on the observations is related to the size, shape, and weight of the product. The solution to the problem taken in this study is to make an ankle-foot design based on anthropometry of Asians, especially Indonesians (Table 1). The steps in making this ankle foot design are shown through the flow diagram in Figure 1.

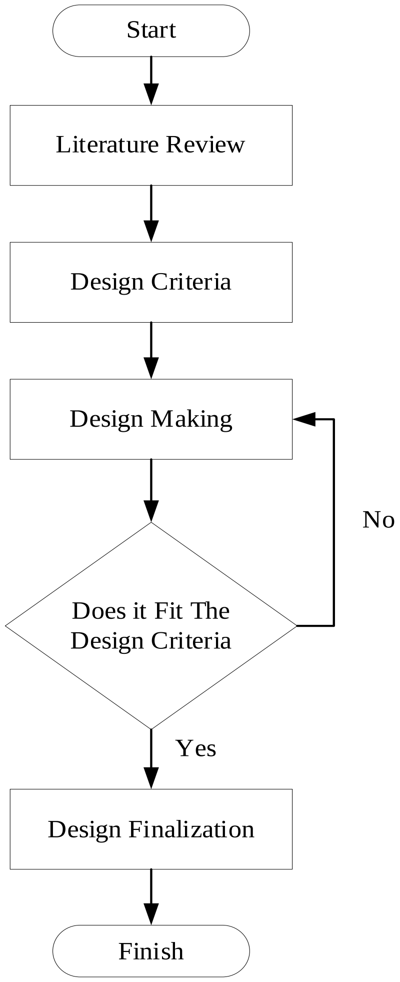

Fig. 1. Research Flow Chart

Based on the flow chart in Figure 1, it is necessary to select criteria for the development of the ankle-foot design. The selection of these criteria is based on pre-existing prosthesis problems. The list of ankle-foot design criteria used as the final goal in this study is presented in Table 2.

Table 1. Anthropometry of Indonesians [14]

Criteria	Minimum Dimension	Maximum Dimension
Height	150 cm	183 cm
Weight	39.8 cm	93.45 cm
Popliteal Height	36 cm	50 cm
Knee Height	42 cm	62 cm
Leg Length	21 cm	29 cm
Feet Width	7 cm	12 cm

Table 2. Design Criteria of Ankle Foot

Criteria	Description
Strength	Able to withstand weight up to 100 kg
Altitude Setting Ability	The prosthesis can be used by both men and women with the provisions of a height between 150 cm - 180 cm
Light	Has a lighter mass than the real leg, which is less than 2.2686 kg [13]
Convenience	Easy to return to a horizontal position when used in walking or standing conditions
Types of Prosthesis	Compliant Mechanism (The design of the fake sole almost resembles the sole of a human foot in general)
Durability	Has a safety factor of four times the maximum load received

A. Load Analysis of Ankle Foot

In making of the ankle-foot design, the maximum human weight is needed to determine the prosthetic foot strength. The prosthesis design is required to have a lower mass than the part of the amputated leg. According to Rajput et al [8] the weight of the leg below the knee has a weight of 5.7% of the human body weight. Meanwhile, according to Chuan et al [12], the maximum human weight is calculated based on Newton's 3rd law, namely:

$$F \quad = m \times g \tag{1}$$

Where F denotes the force in Newtons (N), m is the mass (kg), and g is the gravitational force of the earth (m/s^2). The maximum weight of the prosthesis in this study was calculated based on the formula below:

$$\text{Maximum mass} = 5.7\% \times \text{lowest mass of Indonesians} \tag{2}$$

Where the lowest mass is taken from the anthropometric data that has been obtained. The lowest value is taken because if the highest weight is taken, it will make users who have lower body weight have difficulty in using the prosthesis. Based on the criteria in this study, the user's lowest mass is 39.8 kg, so the ankle-foot prosthesis product must have a maximum mass of 2.2686 kg.

B. Design Specification

The ankle foot design must have elastic properties that are easy to move to carry out daily activities like normal feet. The material used in the ankle foot skin design is silicon rubber. Silicon rubber is a type of synthetic polymer that has several physical properties that are not found in other types of polymers. These physical properties have very special functions and advantages including environmental resistance, extreme temperatures resistance, stability, and non-toxicity. These properties make silicon material suitable for artificial feet and can be shaped to mimic human feet. Furthermore, the material used in the support core must strong, light, and flexible properties as a support, so it's easy to make intensive moves. In this study, we analyze three types of materials to be used in the support core, namely AISI 304, POM (Polyoxymethylene), and ABS (Acrylonitrile butadiene styrene). From these three types of materials will be taken into consideration to choose the lightest material after going through assembly process with the outer skin of the ankle-foot. The properties of each material are shown in Table 3.

Table 3. Materials Properties [14]

Material	Property			
	Density (Kg/m^3)	Young's Modulus (MPa)	Poisson's Ratio	Yield Strength (MPa)
Silicon Rubber	2330	5000	0.28	120
ABS	1020	2300-2750	0.37	26.84
POM	1560	2900-3500	0.42	75.8
AISI 304	8000	193000	0.29	241

C. Design of Ankle Foot

The ankle-foot design in this study was made by developing designs that have been circulating in the market before. The ankle-foot design is made to mimic the human foot in visual using predetermined dimensions. The ankle-foot design is made up of two types, namely the skin part and the core support, which are assembled into one. Improvements made in the development of this ankle foot design are in the geometric dimensions. Geometry measurements on the skin are obtained from the scan results using the Creaform, Ametex. The measurement results of the ankle-foot skin geometry from the scan process are shown in Figure 2. The support core geometry is obtained from the design process using the Solidwork 2017 software. This support core serves to strengthen the prosthesis when it is in a supporting condition and will provide encouragement when going to step. The design of the skin and supporting core in this study is presented in Figure 3. And the design after assembly is shown in Figure 4.

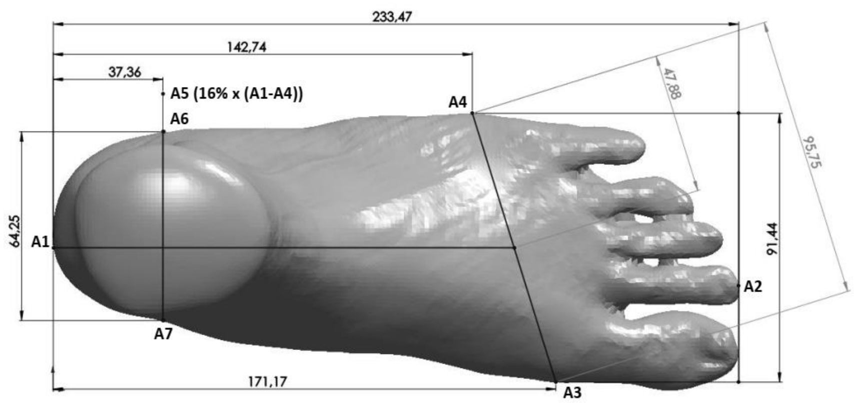

Fig. 2. Foot scan measurement (unit length in mm)

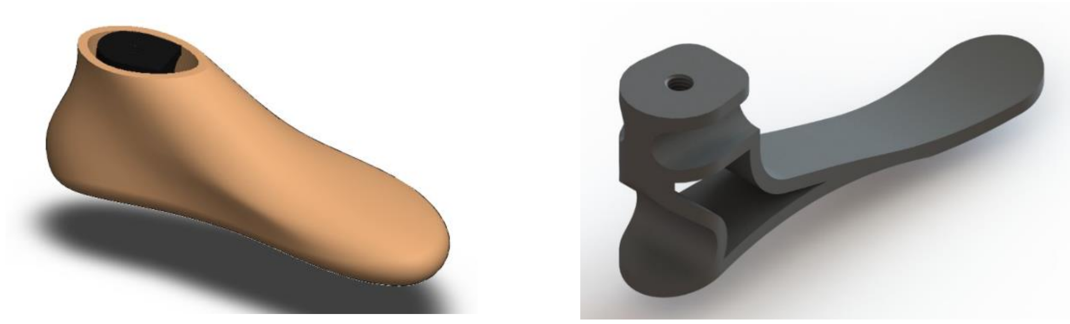

Fig. 3. The design of (a) skin part, and (b) supporting core of ankle foot

Fig. 4. Assembly of ankle-foot design

III. Results and Discussion

Ankle foot prosthesis is very influential for a person with a disability or foot amputation patient in carrying out daily activities, such as walking normally, going up and downstairs, cycling, or performing prayer movements. The ankle-foot design in this study is a development of a pre-existing prosthesis. This development aims to improve the ergonomics of the product, so that it will support the comfort of prosthesis users in carrying out activities. The development is carried out on technical specifications, including geometric design and the type of material used. Design development begins with an anthropometric study of prosthesis users to obtain information on improving technical specifications and obtaining products that meet the criteria through evaluation and design alternatives.

Based on literature studies, data were obtained from human body weight of 89.5 kg and the lowest human weight of 39.8 kg. Human body weight is used as a consideration in designing the ankle-foot strength, where the artificial ankle-foot must be able to withstand the maximum weight of the user. In this study, it was determined that the design criteria of the ankle-foot must be able to withstand a human body weight of 100 kg, and have a maximum mass of 2.2686 kg.

After modeling using CAD software, the ankle-foot design was obtained that matched the criteria, as shown in Figure 3(b). There are several changes when compared to the existing design, including the toe tip to the instep that is designed to be curved like the ankle-foot of a human. It aims to smooth the movement when stepping from the midstance position to the toe-off. The curved shape can also provide additional thrust as the cycle moves from stance phase to swing phase. Furthermore, the hollow design is an application of the compliant mechanism model, where its function is to provide flexibility when the walking cycle movement is carried out. The ankle-foot design was made based on the lowest mass from the anthropometric data of the prosthesis user. The manufacture of this support core is useful as a helper for lifting power against the load from the top of the prosthetic foot. Based on the design analysis, the lowest mass of the ankle-foot prosthesis made is owned by the pair of foot skin products and the supporting core made of ABS. The mass measurement result of the ankle-foot prosthesis in each assembly is presented in Table 4.

Table 4. Ankle Foot Prosthesis Mass

Ankle Foot Prosthesis	Mass (grams)
Silicon + ABS	63.53
Silicon + POM	97.17
Silicon + AISI 304	498.29

V. Conclusions

The prosthesis should be lightweight, durable, and skin-friendly. The combination of intelligent design and materials with a good understanding of the patient's needs, will make the design of the prosthesis more similar to the function and shape of the normal body part. This study presents the ankle-foot design.The new ankle foot design adopts a compliant model mechanism with the aim of making the foot more flexible in walking movements. Based on the research, the design is below the specified criteria, so it can be said that the model has a lightweight nature. The dimensions of the ankle foot prosthesis are based on anthropometric data, so this design is said to be more ergonomic and flexible when viewed from the mass of the prosthesis. The design innovations carried out show that the prosthesis can be used by Asian people, especially Indonesia with a height range of 150 cm to 180 cm and a weight of 39.8 kg to 100 kg.

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