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Evaluation and Improvement of A Prosthetic Hand Product Using Biomechanics and Empathy Map Approach

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Abstract. *The Panangan Prosthetic Hand is a transradial prosthesis that can be operated with both amputated and non-amputated arms. Several users have reported some degree of exhaustion and discomfort when using this prosthesis. Users may also be dissatisfied because this product has not met some of their specific needs and desires. To evaluate the product, tests were conducted by measuring muscle activity using an electromyography (EMG) sensor and assessing discomfort levels using the Borg CR10 scale during specific activities performed with the prosthesis. Additionally, interviews were conducted using an empathy map to profile the participants. The test results showed high muscle activities and discomfort levels in certain tasks, such as pouring water from a drink box. Based on these findings and the participants' profiles, their needs were identified, and solutions for improving the product were designed. Subsequently, these solutions were developed into a three-dimensional computer-aided design (3D CAD) model prototype.*

Keywords: *Borg CR10 scale; EMG; empathy map; prosthesis.*

I. Introduction

Upper limb prostheses are assistive devices for individuals who have lost all or part of their arms, helping them to perform daily activities. However, there are several problems associated with the development of these products in Indonesia. According to Rahman (2017), upper limb prostheses in Indonesia are mostly passive type, only serving as cosmetic aids. Furthermore, they are less effective in facilitating activities and they can cause discomfort when worn for prolonged period due to heat buildup. Additionally, the cost of these prostheses is high, ranging from 7,000,000 IDR to 15,000,000 IDR for a passive upper limb prosthesis in East Java, Indonesia (Gatot, 2017, as cited in Rahman, 2017). In another study, Resnik et al. (2012) reported that in 2011, based on data from the Centers for Medicare and Medicaid Services in New York, the cost of upper limb prostheses with a motion system ranged from 4,000 USD to 75,000 USD.

Currently, there are various innovations in upper limb prostheses to overcome these problems in Indonesia. One of such products is the Panangan Prosthetic Hand, developed by a startup called Idealab.id. This product is a transradial prosthesis designed for individuals with amputations below the elbow. It features a robot-like appearance, intended to boost users' confidence and eliminate the need to conceal their amputated condition. The socket shape, which wraps around the amputated limb, and the length of the pulling rope can be adjusted to cater to individual needs, making it suitable for individuals with transradial amputations in various conditions (Figure 1).

The Panangan Prosthetic Hand is a body-powered prosthesis made of polymer using a three-dimensional printing and thermoforming process. It is capable of performing a gripping movement known as the voluntary closing (VC) mechanism (Sensinger et al., 2015). The gripping action is of the lateral type, where the tip of the thumb touches the side of the index finger (SHAP Business Enterprise, 2022). This movement can be achieved by pulling the attached rope, which is connected from below the prosthesis to the non-amputated arm across the back.

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Figure 1. Appearance of the Panangan Prosthetic Hand: (a) the body of the prosthesis and (b) the socket of the prosthesis

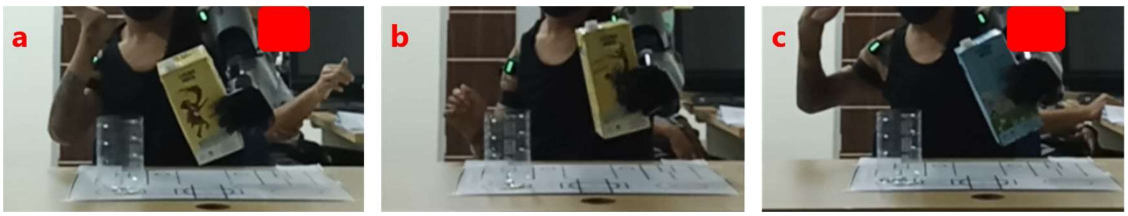

Figure 2. Three kinds of prosthesis operating mechanism during the drink box pouring task: (a) pushing the non-amputated arm forward, (b) pushing the amputated arm forward, and (c) pushing the non-amputated arm sideways

Using unique mechanism (Figure 2), this prosthesis can be operated in three different ways. The mechanism differs from the conventional body-powered prosthesis, which rely solely on the amputated side of the body. However, operating this prosthesis with the non-amputated arm may result in user's fatigue. Furthermore, study conducted by Major et al. (2014) has indicated that the use of conventional upper limb prostheses can increase the range of motion in the shoulder and back during certain activities when compared to data from able-bodied individuals. As a result, utilizing the new mechanism in this prosthesis may require more space for user movement. This issue is further exacerbated by the limited range of motion capabilities of the prosthesis, leading to user difficulties and discomfort during its use.

Based on this information, it is important to evaluate and improve the Panangan Prosthetic Hand product. This evaluation and improvement process aligns with the standards established by the World Health Organization (Eklund & Sexton, 2017), which emphasize the necessity for each country to possess an appropriate prosthesis that caters to its specific needs. Through this process, Idealab.id's services can be enhanced to adhere to Minister of Health Regulation of the Republic of Indonesia No. 27: Standards for Orthotic and Prosthetic Services (2015), thereby ensuring the provision of high-quality services.

This study evaluated the prosthesis using a biomechanical approach to examine the musculoskeletal loading during prosthesis usage. According to Iridiastadi and Yassierli (2014), several factors, including postural stress, forceful exertion, repetitive exertion, static exertion, localized mechanical contact stress, vibration, and cold temperature, can contribute to health problems. Some of these factors may arise during the operation of this prosthesis particularly when certain activities require substantial energy expenditure.

The biomechanical approach involved measuring muscle activity and subjectively assessing discomfort levels during specific activities, as demonstrated in Lee and Jo (2014). These activities can be adapted from Major et al. (2014), which utilized the Southampton Hand Assessment Procedure (SHAP). The SHAP is a collection of daily living tasks designed to evaluate upper limb prostheses and assess medical issues related to hand function (SHAP Business Enterprise, 2022). Therefore, the SHAP is a suitable tool for testing the Panangan Prosthetic Hand.

In addition, this evaluation process was also carried out with interviews to find out the user characteristics. The interview was conducted with an empathy map as in the study of Franata and Setyorini (2020). Empathy map is a tool which developed by XLANE to map personas or user profiles that contain information related to environmental conditions, behaviors, concerns, and aspirations of users (Osterwalder & Pigneur, 2010).

II. RESEARCH METHOD

Data Collection and Analysis

This research utilized the design thinking method as it enables a deep understanding of human-centered problems (Tosi et al., 2020). The study focused on evaluating the performance of a single left-sided Panangan Prosthetic Hand product. Additionally, a three-dimensional computer-aided design (3D CAD) prototype of the recommended solution was created to illustrate the design improvements. The prototype is a flexible and easily adaptable focused analytical prototype type that serves as a learning tool (Ulrich et al., 2020).

Participants completed five tasks adapted from Major et al. (2014) using Panangan Prosthetic Hand. These tasks involved various movements, allowing for the observation of participants' actions and the identification of any potential issues. However, due to a finger breakage incident during the trial, the task involving the movement of heavy objects was replaced with a similar activity from SHAP. The following were the five tasks used in this study, adapted from SHAP Business Enterprise (2022).

a. Lifting and transferring a light object task (T1) – Participants were asked to move an empty jar from the non-amputated side to the front of the amputated side while overcoming an obstacle in the form of a drink box lying in the center.
b. Page turning task (T2) – Participants were asked to move a piece of paper from the non-amputated side to the front of the amputated side while flipping it over.
c. Drink box pouring task (T3) – Participants were asked to pour 200ml of water from the drink box in the center into the container in front of the non-amputated side.
d. Lifting and transferring a tray task (T4) – Participants were asked to transfer a tray with both hands from the front of the non-amputated side to the front of the amputated side.
e. Simulated food cutting task (T5) – Participants were asked to simulate cutting food using plasticine and to pick up a knife placed in front of the amputated side.

The five activity tasks were performed three times each, using three different mechanisms to operate the prosthesis: pushing the non-amputated arm forward (M1), pushing the amputated arm forward (M2), and pushing the non-amputated arm sideways (M3). The length of the pulling rope was standardized across all tests to ensure it did not impede the user's ability to perform the activities. Specifically, the pulling rope length was adjusted so that when the prosthesis arm was fully extended forward and the non-amputated arm was pushed 60 degrees sideways, the prosthesis fingers would grip.

During the test, muscle activity was measured using an electromyography (EMG) sensor called the Trigno Avanti Sensor from Delsys. The sensor is a surface EMG type attached to the skin surface above the muscle being measured.

The EMG sensor was used to measure the activity of the anterior and middle deltoid muscles in both the right and left shoulders. These muscles were selected based on Major et al. (2014), which reported an increase in range of

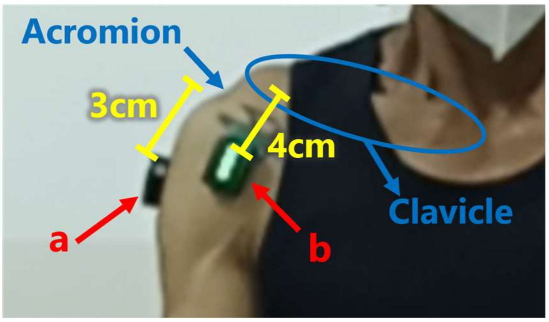

Figure 3. Attachment locations of electromyography (EMG) sensors: (a) middle deltoid muscle and (b) anterior deltoid muscle

motion values, as well as their crucial role in operating the prosthesis. Furthermore, these muscles are not covered by the prosthesis, allowing sensors to be attached without interference during testing. The sensor attachment locations can be found in Figure 3, as indicated in the Delsys sensor usage guide.

Before measuring muscle activity, the maximum voluntary contraction (MVC) was measured for each muscle. This MVC value is used to normalize the data recorded during the muscle activity test, which allows the calculation of the MVC percentage value (%MVC). The average %MVC values for each muscle can be compared to determine which muscles are being overworked or experiencing discomfort (Choi & Lee, 2015).

The %MVC value obtained can be compared for existing data from previous studies to identify potential issues. Shoulder muscles may already experience fatigue during activities involving 5-10% of the MVC value (Caffier et al., 1993; Hansson et al., 1992; Jørgensen et al., 1988; cited in Roman-Liu et al., 2001). According to Roman-Liu et al. (2001), 25 minutes of activity involve contraction of the middle deltoid muscle up to 20% of its maximum can induce muscle fatigue. Additionally, an equation (equation 1) is provided by ACGIH (2016 cited in Gillette and Stephenson, 2019) to calculate the threshold limit value (TLV) of %MVC in the upper limbs during work with a certain duty cycle (DC). The TLV value serves as a limit to avoid the risk of fatigue and health problems. Artifacts in %MVC calculations, such as sensor contact issues (Gillette and Stephenson, 2019) or values exceeding 100%, need to be considered and removed to ensure accurate analysis.

$$TLV = 100 * \left(-0.143 * \ln\left(\frac{DC}{100}\right) + 0.066\right) \quad (1)$$

During the testing process, the level of discomfort was measured using the Borg CR10 scale, as utilized in Lee and Jo (2014). This measurement was intended for the right shoulder (A), left shoulder (B), amputated limb (C), back (D), and any other body parts where participants experienced discomfort. The objects are used in this study were lightweight, similar to those tested in Lee and Jo (2014). Therefore, based on their findings, repeatedly moving a 1kg object would result in a score between 1 and 2 on the Borg CR10 scale for the shoulder. Hence, it can be assumed that participants in this study would have experience a similar level of discomfort while performing the activity under normal conditions.

To ensure equal discomfort perception among participants, a wall squat position (sitting against a wall without a chair) was performed before measuring the level of discomfort. According to Lea et al. (2021), the wall squat position is easy to perform and can quickly induce a high level of discomfort. Participants were asked to rate their discomfort during the wall squat position and during the testing procedure. The reference point for comparison was when the leg could not support the body in the wall squat position, which was considered a discomfort score of 9. This calibration procedure was adapted from Muslim and Nussbaum (2017).

After testing the prosthesis, the participants were interviewed using the empathy map question format (Ferreira et al., 2015; Osterwalder & Pigneur, 2010). The information obtained from these interviews can be used to create a profile map for each participant or a general profile map. According to Osterwalder and Pigneur (2010), the profile map consists of six sections: "see" (what is seen in the environment), "hear" (how the environment affects the individual), "think and feel" (the individual's thoughts and emotions), "say and do" (the individual's behaviors), "pain" (problems and difficulties), and "gain" (desired outcomes).

Based on the results of data collection, an analysis process was carried out to identify the problems experienced by each participant. Since each participant may have experience different problems, alternative solutions may also vary. After designing various alternative solutions, a focus group discussion (FGD) was conducted with Idealab.id to select the best alternative solution that would be made into a prototype. The FGD technique was chosen not only to suit the needs of Idealab.id but also to collect ideas and perceptions from each participant in the FGD, ensuring a productive discussion (Cornwall &

Jewkes, 1995; Hayward et al., 2004; Israel et al., 1998; Kitzinger, 1994; Morgan, 1996; as cited in Nyumba et al., 2018).

After creating the prototype, it is evaluated by soliciting feedback from participants. The feedback is gathered by using the I Like, I Wish, and What If (IL/IW/WI) tool, as utilized in Brink (2021) to gather opinions on new cultural (business) ethics concepts. This tool also has been employed in Alshehri (2020) to gather feedback on the application of design thinking methods in addressing complex dentistry issues. The tool comprises three questions aimed at understanding participants' preferences, expectations, and suggestions regarding the utilized concept or tool. The feedback obtained serves as a reference for enhancing the prototype and making it even better.

Participants

This research involved two adult male participants who had undergone left-sided transradial amputations and had not a history of shoulder-related diseases that could be hinder the use of the prosthesis. These criteria were selected to ensure that the participants were suitable for testing the prosthesis. The limited number of participants was primarily due to the requirement of conducting the testing process in the laboratory, which made it difficult to recruit participants from distant locations.

Although the criteria for participants have been established, there were differences in the conditions of the two participants, as shown in **Error! Reference source not found.**. It is important to consider this information as it may have an impact on the results of data analysis.

III. RESULT AND DISCUSSION

Observation Result

The testing process went smoothly despite the limited mobility of the prosthesis because tasks could be performed without requiring much forearm movement. However, both participants were observed performing additional movements, such as the sideways bending movement is shown in Figure 4. Such as additional movements should be avoided as they can lead to increase fatigue or even injury.

Furthermore, the movements required to perform other daily activities are just not the same as the movements required in this test. Therefore, the prosthesis should be capable of mimicking the movements of a natural forearm, enabling users to easily perform various activities. These movements include bending or straightening the elbow and rotating the wrist.

The difference in the remaining forearm length between the two participants also impacted the operation of the prosthesis. The first participant (P1) had a very short remaining forearm, which lacked the strength to bend the prosthesis elbow. As a result, so P1's left arm was always in a straight position throughout the test. This limitation would be undoubtedly restricted P1's ability to engage in other activities. Therefore, it is recommended to incorporate additional motion mechanisms for users with similar conditions to P1.

Figure 4. Example of performing the task by

According to the assigned tasks, only task T4 could not be performed by the second participant (P2). This shows that the prosthesis is easy to learn and use. P2 encountered difficulties in task T4 as the prosthesis grip frequently slipped off the tray during movement. Additionally, both participants had difficulty gripping the knife (in task T5) because the prosthesis finger grip was not strong enough.

Muscle Activity

A graph depicting the %MVC values of each muscle during the tested tasks can be created based on the measurements of muscle activity, as

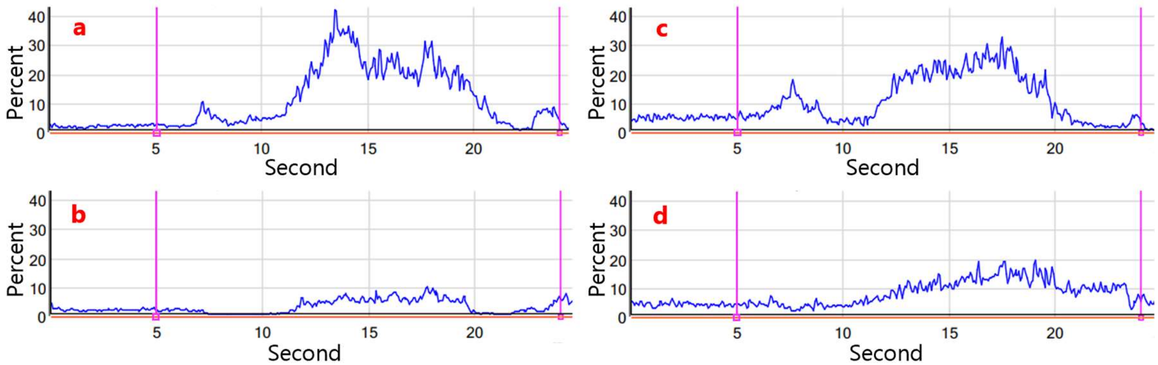

Figure 5. Graphs of percentage of maximum voluntary contraction (%MVC) for each muscle during the first repetition of lifting and transferring a light object task, with the non-amputated arm pushing forward: (a) right anterior deltoid, (b) right middle deltoid, (c) left anterior deltoid, and (d) left middle deltoid

Table 1. Average percentage of maximum voluntary contraction (%MVC) values for each muscle in each test

Task	Muscle	Percentage of Maximum Voluntary Contraction (%)					
		First Participant			Second Participant		
		M1*	M2	M3	M1	M2	M3
Lifting and transferring a light object	RAD*	12.8	7.0	8.1	4.8	0.2	1.7
	RMD	4.3	3.2	9.8	2.5	0.6	5.7
	LAD	12.9	14.1	14.3	7.5	7.3	6.5
	LMD	10.2	12.0	11.4	5.1	5.3	4.8
Page turning	RAD	11.5	3.4	8.1	4.2	0.4	6.6
	RMD	5.4	3.6	9.3	3.5	1.4	16.8
	LAD	8.1	10.4	8.7	12.6	15.4	12.4
	LMD	12.7	12.5	10.6	11.8	15.7	13.0
Drink box pouring	RAD	12.4	6.6	11.2	5.3	1.5	6.2
	RMD	6.0	11.5	13.7	3.0	0.3	18.3
	LAD	13.0	13.6	11.6	23.2	27.7	27.5
	LMD	36.7	42.8	34.6	27.7	30.2	32.0
Lifting and transferring a tray	RAD	13.2	11.5	10.5			
	RMD	14.1	14.9	20.1			
	LAD	12.7	11.0	13.8			
	LMD	9.3	6.4	8.7			
Simulated food cutting	RAD	11.9	6.9	10.3	3.7	4.0	7.9
	RMD	7.5	9.1	13.3	7.5	5.8	20.7
	LAD	11.2	13.1	15.5	14.6	18.7	20.1
	LMD	12.7	11.2	13.9	6.2	9.2	14.0

*RAD = right anterior deltoid, RMD = right middle deltoid, LAD = left anterior deltoid, LMD = left middle deltoid, M1 = pushing the non-amputated arm forward, M2 = pushing the amputated arm forward, and M3 = pushing the non-amputated arm sideways.

that is in Figure 5. The fluctuation in muscle activity corresponds to the movements of the participants' hands. Analysis of the average %MVC values for each muscle reveals no significant increase or decrease between repetitions. This could be attributed to the relatively short duration of the tasks, which may not have induced significant fatigue. The average %MVC values for each test are presented in Table 1.

Examining Table 1, it is evident that the %MVC value for P2 is comparatively lower than that of P1. This discrepancy can be attributed to the fact that P2 has been living with the amputation for an extended period and is accustomed to performing various activities, including strenuous ones. However, it is worth noting that both participants exhibit high average %MVC values exceeding 20% in certain tasks. This indicates that the deltoid muscle is subjected to a considerable workload when using this prosthesis. Apart from individual capabilities, the high values are influenced by the duration of the participant's pull on the prosthesis rope, the height the hand is raised, and the weight of the prosthesis and the object being gripped. One factor contributing to the weight of the prosthesis is the large size of the prosthesis cover (Figure 1.a). Therefore, there is a need for prosthesis improvement and/or adequate rest to prevent excessive shoulder fatigue and potential injuries.

Based on Table 1, it is evident that the left deltoid muscle plays a crucial role because it receives a significant physical workload. The use of the non-amputated arm (right deltoid) to pull the prosthesis rope was observed to reduce the activity of the left deltoid muscle. However, most of the decrease in the left deltoid %MVC value from P1 was lower than the increase that occurred in the right deltoid. Therefore, it is recommended for P1 to use the M2 operating mechanism. Meanwhile, P2 is advised to use the M1 operating mechanism as it has a lower total mean value than the other mechanisms. This advice is because P2 has a much stronger right deltoid muscle compared to the left deltoid, as seen from the very small average %MVC value. This value is even smaller than the data of P1. This finding is consistent with the data on the participant's strongest body side, which was reported by each participant at the beginning of the study (**Error! Reference source not found.**).

Although the best operating mechanism has been determined for each participant, there are discrepancies in the data. This is because the determination process considers the average or majority best value of all the tested tasks. For instance, task T3 resulted in a low %MVC value for P1 when using operating mechanism M1. This occurred because task T3 required the participant to use the amputated arm for an extended period, which imposed a significant load on the amputated arm. However, despite the observed discrepancy, the decision regarding the variation of the prosthesis operating mechanism remained

Table 2. Borg CR10 scale values of each prosthesis operating mechanism

Tasks	Mechanism	Level of Discomfort										
		First Participant						Second Participant				
		A*	B	C	D	E	F	A	B	C	D	G
T1*	M1*	3	3	3	3			0	0	0	0	1.5
	M2	3	3	3	3			0	0	0	0	1.5
	M3	3	3	3	3			0	0	0	0	
T2	M1	3	3	3	3	0.5	1	0	2	0	0.5	
	M2	3	3	3	3	0.5	1	0	0	0	0	
	M3	3	3	3	3	0.5	1	0	0	3	0	
T2	M1	3	3	3	3		4	0	0	0	0.5	
	M2	3	4	4	3		4	0	0	0	0	
	M3	4	4	4	0.5	3	5	0	0	0	0.5	
T2	M1	3	0	3	0	3						
	M2	0	3	3	0	3						
	M3	3	4	3	0	0.5						
T2	M1	3	4	3	0			0.5	0	0	0	
	M2	0	3	3	0			0	0	0	0	
	M3	4	4	4	0.5			0	0	0	0	

*T1 = lifting and transfering a light object, T2 = page turning, T3 = drink box pouring, T4 = lifting and transferring a tray, T5 = simulated food cutting, M1 = pushing the non-amputated arm forward, M2 = pushing the amputated arm forward, M3 = pushing the non-amputated arm sideways, A = right shoulder, B = left shoulder, C = amputated section, D = back, E = left waist, F = right waist, and G = right shoulder blade.

Table 3. Mapping results of participant profiles

Mapping Section	First Participant's Profile	Second Participant's Profile
See	- Children enjoy seeing my amputated limb. - A prosthesis prevents the hand from appearing empty. - I seldom go out. - My wife enjoys helping with activities.	- The amputee may choose to wear something to conceal their amputation. - I seldom go out. - My coworkers like to help me when we work together.
Hear	- The expensive robotic prosthesis is reported to be uncomfortable to use. - The claw or hook-shaped tip of the prosthesis looks intimidating.	- There are few amputees in my local area. - A finger-shaped prosthesis tip is preferable to a claw-shaped tip.
Think and feels	- An upper limb prosthesis is necessary for moving objects. - A passive prosthesis is simple, but it can be uncomfortable, heavy, and smelly. - If the pulling rope is used with the left arm, the object will be pushed, while if it is used with the right arm, it will look awkward. - The appearance of the tested prosthesis resembles that of a robot. - It's a waste if the prosthesis is seldom used.	- An upper limb prosthesis is important if it can function properly. - Passive prostheses are uncomfortable and cannot be used for activities. - Using the right arm to pull the rope sideways may look strange. - The tested prosthesis looks good and resembles a robot. - During the test, I was not yet familiar with the prosthesis being tested.
Say and do	- The amputated area can become painful during strenuous activities. - The left arm can still assist with activities, but if the activity is still difficult, modify the tool to make it easier. - Had participated in rehabilitation program. - Wear a vest to cover the rope of the prosthesis on the back. - I used to work as an installer of Wi-Fi, but now he is starting a new business.	- The amputated area can be painful during strenuous activities. - Before the pandemic, I worked on a construction project. - Activities after amputation are not significantly different from those before amputation. - The left arm can still be used to perform activities. However, if the activity is still difficult to do, then I may use my foot for assistance. - The tested prosthesis is easy to wear, except for the bonding part.
Pain	- Taking care of the body and wearing a prosthesis still require assistance. - Before attempting to take an object with a prosthesis, I must think first. - There are still wounds on my body. - I can't bend or straighten the elbow on my prosthesis. - The prosthesis is not very durable.	- I cannot carry heavy objects or do activities that require both hands. - The grip strength of the prosthesis is not strong enough. - The prosthesis is unable to pick up thin objects.
Gain	- The prosthesis should be capable of picking. up various types of objects and assisting the non-amputated arm. - A comfortable prosthesis should not be heavy or cause pain. - The price of the prosthesis should be affordable or credible.	- The prosthesis should be stronger to lift objects. - The prosthesis should be able to rotate and flip the palm. - The prosthesis can be used for various activities. - The price of the prosthesis is affordable.

unchanged. If the chosen prosthesis operating mechanism is suitable for performing the majority of tasks in this study, which involve different movements, it is expected to provide a sense of comfort and safety during various other activities.

If participants encounter activities that are difficult or strenuous to perform with the specified operating mechanism, it is recommended that participants refrain from exerting themselves and take adequate rest to avoid injury or damage to their hand. The length of the rest period can be determined based on equation (1) or based on the individual needs of each participant.

Level of Discomfort

Based on Table 2, it is evident that P1 experiences a higher level of discomfort compared to P2. P1 also experiences discomfort in a greater number of body parts compared to P2. These can be attributed to the presence of wounds on P1 (as indicated in **Error! Reference source not found.**). Additionally, as a relatively new amputee, P1 may be less accustomed to performing physical activities. The discomfort value measured for P1 is also higher than the value reported in the study conducted by Lee and Jo (2014). Therefore, it is crucial to make improvements to the prosthesis, particularly in addressing the body parts that exhibit a high level of discomfort.

During the testing, both participants provided feedback. According to them, M2 was considered the easiest prosthesis operating mechanism, while M3 was considered the most difficult. Both participants experienced trembles

Table 4. List of usage needs for transradial prosthesis and their fulfillment status in the tested prosthesis

No	Participants' Needs	Status
1	The prosthesis can securely hold various types of objects, including knives and thin items.	PF
2	The prosthesis is designed to stay firmly in place when worn.	PF
3	The prosthesis can supplement the function of the remaining arm.	PF
4	The prosthesis is lightweight.	AF
5	The prosthesis is designed to avoid causing irritation to the amputated limb.	AF
6	The prosthesis can be used for a variety of activities, such as self-care and work-related tasks.	PF
7	The prosthesis does not cause discomfort or pain in other parts of the body.	PF
8	The cost of the prosthesis is affordable.	AF
9	The prosthesis is easy to put on and take off.	PF
10	The prosthesis has strong durability, including the fingers that are less prone to breakage.	PF
11	The prosthesis is easy to operate.	PF
12	The prosthesis provides a sense of confidence to the user in public places, as it has a robotic look and finger shape similar to a natural finger.	PF
13	The prosthesis is capable of lifting objects without requiring the user to move them to the edge of a surface first.	PF
14	The prosthesis does not cause difficulty when putting on or taking off clothes.	PF
15	The prosthesis has a strong and non-slip grip.	PF
16	The prosthesis requires minimal effort to move the fingers, as the rope does not need to be pulled far.	PF
17	The prosthesis prevents objects from being pushed forward when held.	PF
18	The prosthesis can perform rotating and flipping movements of the palm.	UF
19	The prosthesis is designed to protect the amputated part from impact.	AF
20	The prosthesis allows user to perform movements at the elbow, even with minimal remaining forearm (first participant only).	UF
21	The prosthesis rope is designed to be pulled with a forward movement of users amputated arm (first participant only).	PF
22	The prosthesis has a longer rope to accommodate larger body sizes (second participant only).	AF
23	The prosthesis rope is designed to be pulled with a forward movement of users non-amputated arm (second participant only).	UF
24	The prosthesis can lift heavy objects (second participant only).	UF

*AF = already fulfilled, PF = partially fulfilled, and UF = unfulfilled.

in their left arms when they held longer and heavier objects (as shown in Figure 4). P1 even reported experiencing a tingling sensation in the amputated part as a result.

The level of discomfort values on the right and left shoulders for each task did not match the %MVC values. For example, the level of discomfort values on the right and left shoulders from task T1 for P1 were all 3, whereas the %MVC values varied depending on the prosthesis operating mechanism. This is because the level of discomfort values is measured from body parts, which consist of several muscles, while the %MVC value is measured for a specific muscle only. Additionally, the mismatch between these two values may occur because the tasks in the test are quite quick and easy to perform, making it difficult for participants to distinguish discomfort. Therefore, the determination of the prosthesis operating mechanism was chosen based on the %MVC value alone. Nevertheless, the level of discomfort value still has an important function in this study, which is to determine the discomfort that occurs in body parts that cannot be measured by EMG sensors.

Participants Profile Map

Table 3 shows the profile information of each participant. From this information, it is apparent that the Panangan Prosthetic Hand product still

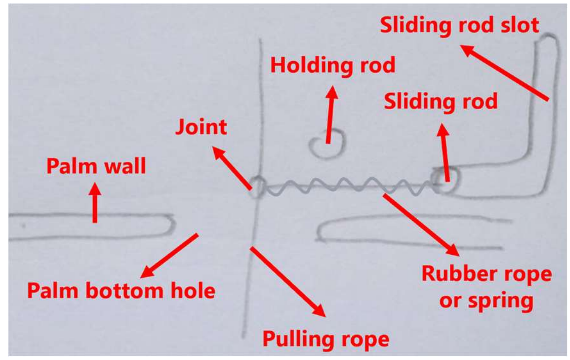

Figure 6. Design of components for controlling the finger movement mechanism inside the prosthesis palm

has some limitations in meeting the needs of the participants, such as inability to perform certain activities that require a strong grip and movement at the elbow. P1 has more needs due to other injuries in his body, which limit his ability to perform various activities. Nevertheless, this product has successfully fulfilled some of the participant's needs and desires, including the ability to move and an attractive appearance.

Needs

Based on the analysis results, all the participants' prosthesis usage needs can be seen in Table 4. However, it is evident that there are several needs that have not been fulfilled or have only been partially fulfilled by the Panangan

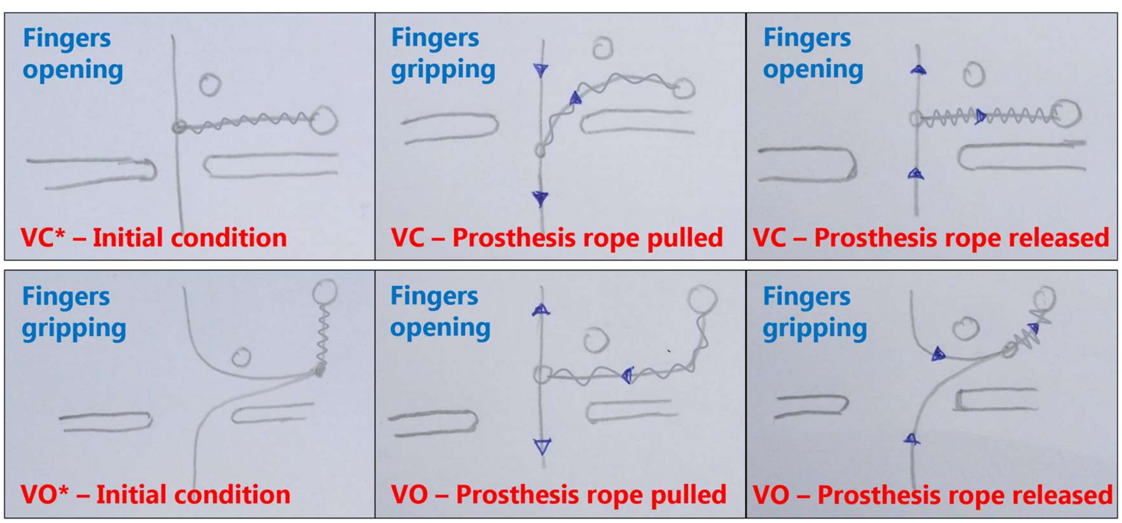

Figure 7. Overview of the two mechanisms for pulling the rope to move the prosthesis fingers
*VC = voluntary closing and VO = voluntary opening.

Prosthetic Hand product. Therefore, further improvements are required for this product. Nevertheless, the product is still suitable for use as it has fulfilled some of the participants' needs.

Solutions

Alternative solutions were developed to address the needs of each participant. These solutions were designed based on existing concepts and solutions that could be applied to the prosthesis. For example, Sensinger et al. (2015) suggested incorporating two finger movement mechanisms in the prosthesis arm: voluntary closing (VC) for gripping, where the

Table 5. List of recommended solutions to fulfill user needs

No	Recommended Solutions	Fulfilled Needs (from Table 4)
1	Adding a sliding rod to adjust the prosthesis finger movement mechanism (voluntary closing and voluntary opening).	3, 6, 7, 11, and 16
2	Utilizing a camera tripod model to adjust the palm position for easier object grip.	6, 7, 11, and 18
3	Adding a gear wheel inside the prosthesis to enable slight pulling of the rope to close the fingers of the prosthesis.	11, 15, and 16
4	Adding a rotating mechanism for the thumb (through hitting or sliding) to enable lateral gripping motion (as it currently is) and pinching motion.	1, 6, 7, 11, 15, and 18
5	Utilizing a shoulder brace product model to facilitate the wearing of the prosthesis.	9 and14
6	Changing the position of the prosthesis pulling rope to the outside hand to prevents the socket connection from opening.	2
7	Adding circular ties to the prosthesis forearm to securely attach the prosthesis to the user's hand.	2
8	Strengthening the ropes on the prosthesis fingers by joining several ropes together.	10
9	Replacing the components on the prosthesis with stronger materials to prevent damage, especially on the finger joints.	10
10	Making the prosthesis rope for the first participant retractable without needing to be tied to the non-amputated arm, similar to the rope model on the heavy-duty prosthesis in Fryer (1992).	3, 7, 9, 11, 12, 14, 16, 17, 21, and 22
11	Designing a vest-like cover to conceal the awkward appearance of the rope on the user's back.	12
12	Adding a mechanism to enable bending or straightening of the prosthesis elbow using shoulder motion for the first participant, similar to the upper elbow prosthesis model described in Fryer (1992).	6 and 20
13	Developing a nail-like tool to facilitate picking up small objects.	1, 6, and 13
14	Designing the prosthesis and the pulling rope to be easily disassembled and assembled, to facilitate wearing and adjusting the pulling rope length.	9, 12, and 14
15	Enhancing the gripping strength of the prosthesis fingers.	15
16	Adjusting the length of the pulling rope on the back of the prosthesis for the second participant to accommodate the user's body size.	22 and 23

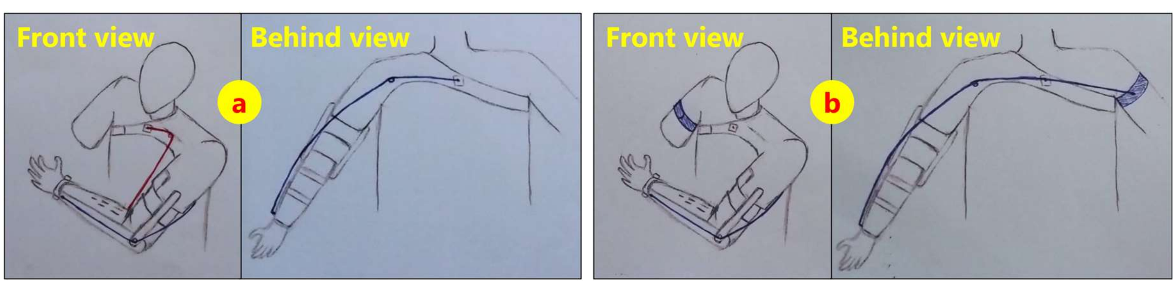

Figure 8. Pulling rope models for prototype: (a) first participant's model and (b) second participant's model

fingers naturally rest in a releasing position, and voluntary opening (VO) for releasing the grip, where the fingers naturally rest in a gripping position. Each mechanism has its own advantages and disadvantages, allowing users to adjust the type of finger movement mechanism according to their needs. This aligns with the findings of our study, where the high %MVC value was attributed to participants needing to grip objects by pulling the prosthesis rope. By incorporating the VO mechanism, users would no longer need to pull the prosthesis rope when lifting or moving objects. The design implementation of the VC and VO mechanisms for a prosthesis with finger-like structures resembling human fingers can be seen in Figure 6 and Figure 7. The switching between VC and VO mechanisms is achieved by sliding the sliding rod (shown in Figure 6) with the assistance of another hand or person.

In this process, need number 24 in Table 4 and the need for self-care (part of need number 6 in Table 4) cannot be fulfilled. This is because suitable literature and concepts have not been identified yet. Additionally, lifting heavy objects poses risks to the user's body, particularly the amputated part. Furthermore, activities related to body care, such as cleaning the ears, cannot be accomplished as they require precise finger motion control and strength. Engaging in these activities alone could be hazardous for participants. Therefore, it is advised that participants avoid performing these activities without assistance.

After all the alternatives were designed, a FGD was conducted with Idealab.id to determine the best alternative. The results of the best alternative can be seen in Table 5.

Prototype

The prototypes were designed based on Table 5, except for numbers 8, 9, 11, 15, and 16, which were difficult to represent in three-dimensional form. The difference between the prototypes for participants P1 and P2 lies in the model of the pulling rope. The prototype for P2 does not incorporate solutions number 10 and 12 from Table 5, while the prototype for P1 does not incorporate solution number 16 from Table 5. An overview of the different models of the pulling rope prototypes can be seen in Figure 8. To cater

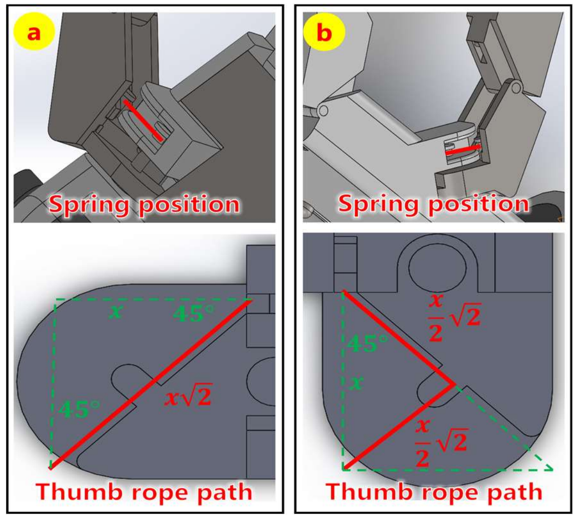

Figure 9. Detailing of the thumb base: (a) lateral gripping motion position and (b) pinching motion position

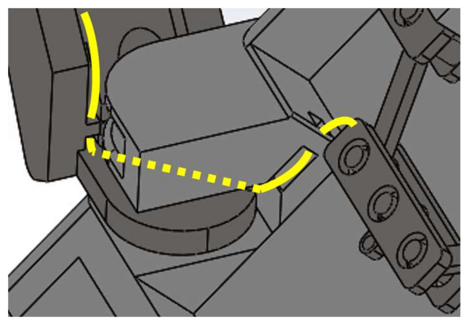

Figure 10. Path of the thumb rope to the whipple tree in the lateral grip position

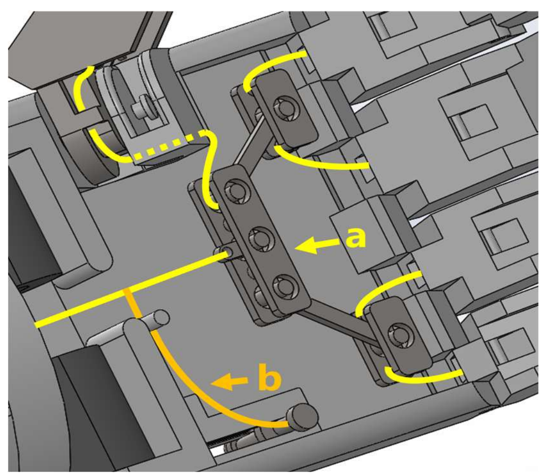

Figure 11. Palm interior details: (a) whipple tree mechanism components and (b) fingers movement type control components

Table 6. Participants' feedback on the initial prototype by using I Like, I Wish, and What If tool

Aspect	First Participant's Feedback	Second Participant's Feedback
I Like	- I like the robotic appearance of the prototype. - I like the use of the shoulder brace which is said reduces fatigue. - I like the grip that can be clenched. - I like the operating mechanism. - I like the presence of fingernails that can be used to pick up coins or credit cards. - I like the adjustable thumb mechanism. - I like the front pulling rope as it helps with elbow movement. - I like the rotatable wrist mechanism.	- I like the shape and color of the prototype. - I like that prototype has more movement. - I like that it's not complicated to use.
I Wish	- I wish this prototype could be produced so that I can try it out. - I wish this prototype could be used daily for various activities. - I wish this prototype could boost my confidence.	- I wish to be able to use this prototype for light work, as it doesn't seem capable of handling heavy work.
What If	- The ventilation part should be replaced with small lines (like a lattice) so that the amputation part is not easily touched from the outside. - It would be better if gloves are not necessary because the fingers already good.	- If it wears gloves, it is better to have the same color as skin. However, if it doesn't wear them, it's okay as long as it's not slippery.

to individual user needs and facilitate the production process, the pulling ropes are designed to be disassembled and adjusted. Additionally, the participants' body measurements were taken to determine the size of each participant's prototype. It is essential to customize the prototype size to ensure ease of wear for participants and a more realistic hand-like feel.

In designing this prototype, the process of detailing components such as color and shape was also carried out. Both participants said that the current prosthesis color was already good, so the prototype color was designed to be similar. Meanwhile, an example of detailing the prototype shape was done on the thumb base. The thumb base is designed to be rotatable so that it can perform a lateral grip (current grip) and a pinch-like grip. The thumb should also not wiggle easily, so it needs anchoring such as a rubber rope or spring. In addition, the length of thumb rope path should also be considered so that the thumb can still be moved in both grips. The detailing result of the thumb base component can be seen in Figure 9 and Figure 10.

Additionally, adjustments and additional components were made in the prototype design, such as replacing the components or mechanisms that allow the pull rope to move the prosthesis finger. The current mechanism is located around the prosthesis wrist, but its details are kept as a company secret. Therefore, a similar mechanism was adapted from Cuellar et al. (2019), specifically the whipple tree mechanism, which is more space-efficient as it can be placed inside the prosthesis palm. However, this mechanism cannot move the thumb, so adjustments were made to enable it to move all fingers. Figure 10 and Figure 11 show the appearance of the adapted mechanism and the adjustment of the thumb rope path.

Adjustments were made to the forearm shape and the socket. The forearm shape was modified from being composed of four small blades and a large cover (shown in Figure 1.a) to being comprised of five large blades only. These five blades also serve as covers, resulting in a

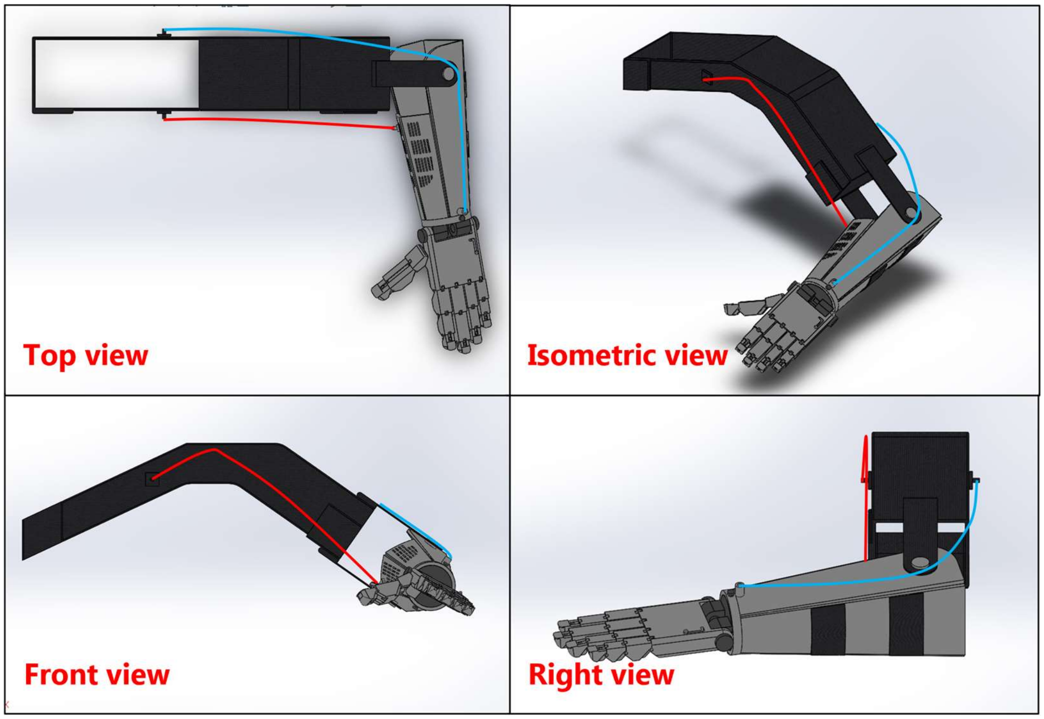

Figure 12. View of the final prototype with the pulling rope model of the first participant

smaller and lighter prosthesis. The blades are connected at the base (wrist), and the diameter of the forearm can be adjusted by manipulating the strap on the bottom blade. Furthermore, the top two blades feature ventilation holes to prevent the user's arm from overheating. On the other hand, the socket was enhanced with an additional hook and loop fastener for clothing, ensuring a more secure attachment to the prosthesis body.

After designing the prototype, feedback was requested from participants using the IL/IW/WI tool. The feedback (Table 6) showed that no new problems were found, and only minor improvements were suggested for the prototype. Therefore, the study process could be concluded. The final prototype, based on participant feedback, is shown in Figure 12.

IV. CONCLUSION

The Panangan Prosthetic Hand is a transradial prosthesis that fulfills some of the participants' needs. However, this study identified some issues with the product and unfulfilled participant needs. Tests revealed a significant increase in %MVC values of the deltoid muscles, particularly during the task of pouring water from a drink box. Additionally, discomfort measurements indicated high values in several body parts, particularly for P1. These elevated values may be attributed to the limited motion cpabilities provided by the prosthesis, limiting its usability for activities that require a strong grip or the ability to handle various objects. Consequently, users may encounter difficulties, discomfort, or fatigue when utilizing the product for such activities. To address these issues, a set of recommended solutions and prototypes were developed to enhance the Panangan Prosthetic Hand. The proposed solutions encompassed sixteen improvements. The prototype incorporating these solutions received positive feedback from participants, with only a few minor suggestions.

Idealab.id needs to make product adjustments based on the results of this study, such as customizing the pull rope model for each user. The customization process can follow the method used in this research. However, since EMG sensors were expensive, Idealab.id can consider using other alternatives, such as the information obtained from this research. The study found that using the P2's pulling rope model is better for users whose strongest side is the non-amputated side. Moreover, since the recommended solution includes a disassemblable pulling rope for the prosthesis, users can buy both rope models and adjust them as needed.

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