

Development of Adjustable Static Test Equipment for Below-Knee Prosthetic Feet: A Case Study

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ABSTRACT

The high prevalence of physical disabilities in Indonesia, particularly among the productive-age population, highlights the urgent need for advancements in prosthetic technology. While local fabricators have begun producing prosthetic feet, the lack of standardized testing procedures compromises safety and performance. This study addresses that gap by developing an adjustable static testing device tailored for below-knee prosthetic feet, focusing on keel and heel tests to evaluate mechanical performance. The device includes a jig-fixture platform adjustable to 8° and 15° for heel and keel tests, respectively. It applies a 1230 N load based on AOPA standards and integrates load and displacement sensors for accurate data acquisition. Structural components are constructed from AISI 1020 steel, with fabrication involving welding, assembly, and system calibration. The testing procedure adheres to ISO 10328 to ensure reliability under realistic loading conditions. An Ottobock SACH prosthetic foot was used in trials, demonstrating the device's ability to classify prosthetic feet into dynamic and cushioned types, based on load-bearing and energy-return characteristics. Polynomial regression analysis showed high accuracy in capturing load-displacement behavior, with R² values above 0.85 for both tests. The results offer valuable guidance for local prosthetic fabricators aiming to design testing equipment or apply AOPA and ISO standards for quality assurance. This research supports the development of a standardized testing framework for prosthetic feet in Indonesia, enhancing product safety and quality while promoting alignment with international benchmarks. The outcomes also suggest potential for broader applications in advancing prosthetic technologies and establishing national standards.

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Keywords: Heel test, ISO 10328, keel test, prosthetic foot, static testing device.

I. Introduction

A large proportion of the working-age population in Indonesia lives with disabilities that make daily activities a challenge. Government data shows that 0.32% of the Indonesian population has feet disabilities. Mobility and independence can be severely limited for those with lower limb amputations. In addition, socio-cultural and environmental challenges further limit their participation in daily activities. This indicates a need for well-designed and personalized prosthetic devices to improve their quality of life [1],[8],[9]. Research has shown that people with mobility impairments frequently struggle with everyday tasks, including basic activities of daily living (ADLs) and instrumental activities of daily living (IADLs). Moreover, community support systems and wide-reaching rehabilitation programs play a crucial role in improving the quality of life for individuals with disabilities, especially in low- and middle-income countries where resources are often limited [2],[3],[10],[11].



Fortunately, Indonesia has seen promising growth in the production of prosthetic feet, with local fabricators stepping up to meet this demand. Indonesia has locally fabricated prosthetic feet. The development of prosthetic foot components has been carried out in the past few years [20]. Innovation in the field of additive manufacturing (AM) is able to make the fabrication process more precise, fast, and affordable, especially in the fabrication of prosthetic sockets and other prosthetic foot components. In addition, it is also able to increase accessibility and customization for users [21].

One of the most difficult challenges in prosthetic leg development is the standardization of testing. Without clear standards regarding the assurance of safety, durability, and performance. Prosthetic leg products can interfere with the comfort and level of user confidence. In addition, without this standard policy, it certainly also has an impact on the inconsistency of product quality, which can have serious consequences for individuals who rely on these devices for mobility and independence [6],[7].

In particular, the International Organization for Standardization (ISO) has standards for structural testing of prosthetic devices, ISO 10328. This standard provides the outline required for testing prosthetic legs. This standard ensures the reliability and safety of prosthetic feet in several variations of loading conditions [12]. This standard is very important because it is a benchmark for assessing the mechanical properties of prosthetic feet products. In addition, the American Orthotic and Prosthetic Association (AOPA) also provides an outline related to testing procedures by classifying prosthetic feet based on loading and unloading performance criteria, including energy return and deflection response. Several empirical studies have shown that these features are critical to improve gait efficiency and satisfy user needs [14]-[18].

Despite all the efforts in the prosthetic industry, there are quite a few challenges, especially in Indonesia, regarding quality assurance and standardized testing of prosthetic feet. A static testing machine for prosthetic feet should be designed and developed in order to overcome these challenges and generally improve the quality of prosthetic devices on the market. The purpose of this research is to eliminate the shortcomings in the prosthetic sector of Indonesia by developing and introducing a testing tool that uses mechanical components, such as linear actuators, to mimic human ground reaction force and apply a maximum force of 1230 N. The approach is aligned with AOPA and international standards, specifically ISO 10328, which specifies a systematic procedure for the testing of lower-limb prosthetics to ensure their reliability and safety under various loading conditions [19]. The present research focuses testing the feature of adjustable static test equipment for below-knee prosthetic feet on keel and heel testing based on international standards to test an Ottobock SACH prosthetic feet in order to not only fill the existing gaps in the Indonesian prosthetic field but also lay a ground for further developments in the field of prosthetic technology and fabricating procedures.

II. Material and Methods

1. Design Criteria

This design is based on several criteria that must be present in a prosthetic leg performance testing machine. This testing machine must be able to provide a load and unload with a maximum load of 1230 N on the prosthetic leg sample. This machine is also equipped with a load sensor and a displacement sensor. The design of the machine also allows adjustment of the jig-fixture platform angle that can be set to angles of 8° for the heel

test and 15° for the keel test, so that it can be used to effectively test the flexion properties of the prosthesis leg. The criteria used in this design are shown in Table 1.

Table 1. Design criteria

Criteria	Description
Strength	Can transfer a load of 1230 N
Testing	Keel test (15°) and heel test (8°)
Measurement system	Load sensor and displacement sensor
Adjustability	The testing device must accommodate prosthetic feet of various sizes and designs. It includes adjustable fixtures and bottom offset adjuster to ensure proper alignment and positioning of the prosthetic foot during testing.

2. Materials and Components

The materials and components used in the development of the static testing device for prosthetic feet are selected based on their mechanical properties, durability, and suitability for the intended purpose of accurate testing. The main materials and components involved in the construction of the device include:

1. AISI 1020 steel (structural material)
 - Column material: Hollow square section, 30 mm × 30 mm, wall thickness 3 mm
 - Base and mounting plates: Flat AISI 1020 steel; thickness 10 mm; tensile strength of 441 MPa; yield strength of 346.5 MPa.
 - Function: Provides rigid support for the test rig under cyclic loading
2. Linear actuator (force application mechanism)
 - Maximum thrust force: 1500 N; Stroke length 100 mm; Input Voltage: 12–24 V DC; Speed: ~5–10 mm/s under full load.
 - Function: Applies controlled loading and unloading to simulate gait forces
3. Load sensors (force measurement)
 - Type: S-type or inline load cell; Rated capacity: 2000 N; Accuracy: ±1% full scale.
 - Function: Measures the vertical load applied to the prosthetic sample
4. Displacement sensors (position measurement)
 - Type: Linear potentiometer or LVDT (Linear Variable Differential Transformer)
 - Stroke range: 0–100 mm; Resolution: ±0.01 mm.
 - Function: Measures vertical displacement during loading/unloading.
5. Fixture and jig components (support and positioning)
 - Standard reference: Designed according to ISO 10328:2016
 - Adjustability: Angular configuration for testing; Heel test: 8°; Keel test: 15°; Foot positioning tolerance: ±2 mm
 - Function: Holds the prosthetic foot securely during loading
6. Electrical and control system (system integration)
 - Function: Controls actuator motion

3. Fabrication Process

The fabrication of the static testing device for prosthetic feet involves multiple stages, each carefully designed to ensure precision, durability, and functionality. The process is divided into the following key steps:

- 1) Conceptual design and planning. The fabrication process begins with the conceptualization and design of the device using computer-aided design (CAD) software. The structure, components, and mechanical systems are modeled to meet the specified design criteria. The CAD model ensures that all components have accurate dimensions and can be assembled properly. The design of the prosthetic testing machine is presented in Figure 1.

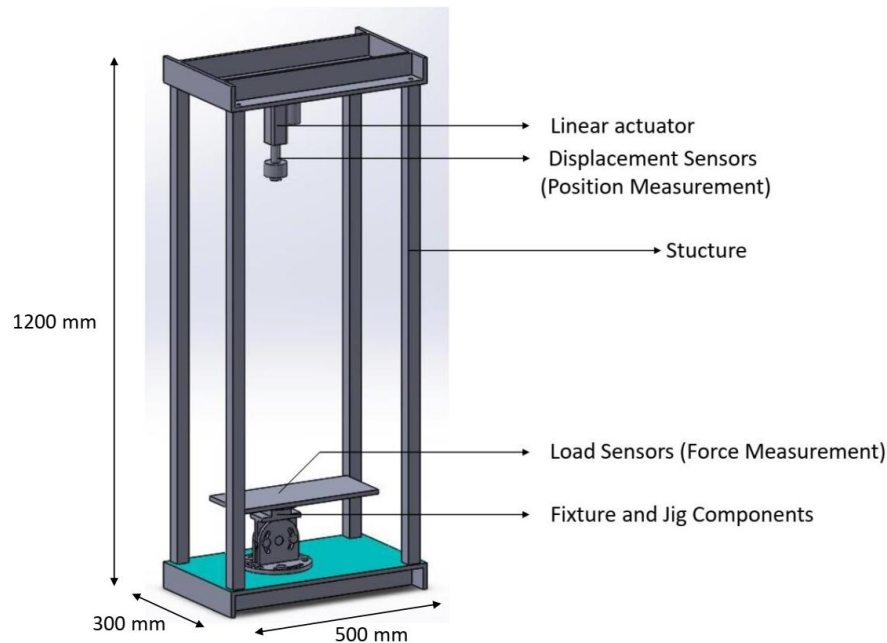


Fig. 1. Prosthetic testing machine design (author illustration)

- 2) Material preparation. Main material includes AISI 1020 for the structural frame and components such as linear actuator, sensor, and fixture. Steel sheet and hollow profile are measured and marked according to dimensions as stated in the design specifications.
- 3) Cutting and shaping. Structural components were cut and shaped to the required dimensions using cutting tools.
- 4) Welding and joining. The structural components were assembled and joined using the metal inert gas (MIG) welding method. This method provides a strong and durable connection. The sequence at this stage includes welding the base frame to provide a solid foundation, assembling brackets and mounting points for sensors and actuators, and adding reinforcements in high-stress areas.
- 5) Assembly of components. The mechanical and electrical components were installed. The actuator is mounted onto the frame and connected to the power supply and control system. Its alignment was carefully checked to ensure smooth and precise operation. Load sensors and displacement sensors were securely mounted at designated locations to collect accurate data during testing. Adjustable jigs and clamps were installed to hold the prosthetic foot in place during tests. These components were tested for stability and adaptability to accommodate various prosthetic foot designs.
- 6) System calibration and testing. The device was calibrated to ensure all components function as intended. Calibration steps include testing the actuator's range of motion and load application accuracy, verifying the sensor's ability to measure forces and displacements accurately. Adjusting the jigs and fixtures to ensure proper alignment, angle, and stability.

4. Testing Protocol

A prosthetic foot testing protocol was developed to provide an accurate, repeatable, and comprehensive performance assessment under loading conditions as per ISO 10328. The protocol includes jig and fixture setup, loading procedures, data collection, and interpretation of results. The protocol includes specific steps for two main tests: the heel test (8°) and the keel test (15°), as shown in Figure 2. The tests were performed in a gradual loading and unloading cycle. An example of a target graph is shown in Figure 3.

The collected data was analyzed by fitting a polynomial regression model to the force-displacement curves for both loading and unloading. The area under the curve (AUC) was calculated using trapezoid calculation in Eq. (1) for each phase to determine the total energy absorbed and returned [22]. The hysteresis loss was obtained by measuring the difference between the two areas, representing the energy dissipation during cyclic loading. Displacement data will be analyzed based on the AOPA standard to evaluate the performance and energy return efficiency of the prosthetic feet (Table 2).

$$\int_a^b f(x) dx \approx (b - a) \frac{f(a)+f(b)}{2} \dots\dots\dots (1)$$

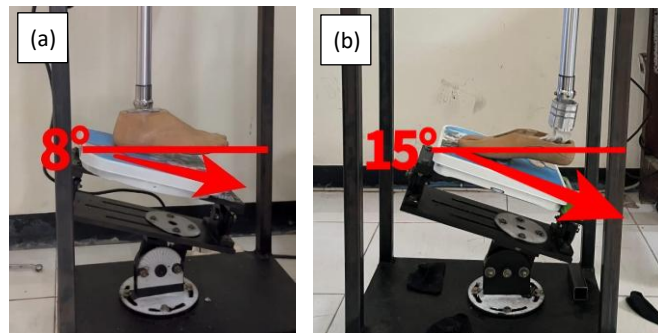


Fig. 2. Heel test (a); and Keel test (b); Adjustable jig and fixture setup (author documentation)

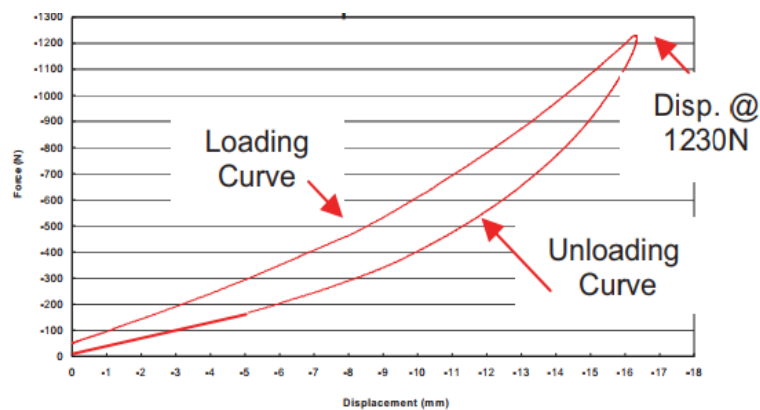


Fig. 3. Loading and unloading graph

Table 2. Classification of keel and heel categories by the AOPA standard

Keel type	Displacement @ 1230 N	Return	Heel type	Displacement @ 1230 N	Return
Rigid	< 25 mm	NA	Dynamic	≥ 13 mm	≥ 82%
Flexible	≥ 25 mm	< 75 %	Cushioned	Does not meet the displacement criteria	
Dynamic	≥ 25 mm	≥ 75 %			

III. Results and Discussions

1. Heel Test

The heel test aims to measure the ability of the prosthetic heel to absorb load and provide stability during the heel contact phase with the ground, while the keel test focuses on evaluating the forefoot of the prosthetic foot in supporting thrust and load distribution during the thrust phase. The results of the Heel Test provide important insights into the performance of the prosthetic foot under various conditions of use, as well as assisting in identifying potential areas of improvement to increase efficiency and comfort for the user. Heel test results can be seen in Table 3.

Table 3. Heel test data

Attempt1			Attempt 2			Attempt 3		
Load (N)	Displacement (mm)	ΔD (mm)	Load (N)	Displacement (mm)	ΔD (mm)	Load (N)	Displacement (mm)	ΔD (mm)
50	28.64	6.19	50	28.74	5.09	50	27.24	2.59
250	34.83	4.91	250	33.83	3.71	250	29.83	2.81
450	39.74	3.89	450	37.54	5.24	450	32.64	3.84
650	43.63	3.07	650	42.78	2.91	650	36.48	2.95
850	46.7	1.61	850	45.69	1.42	850	39.43	2.68
1050	48.31	1.66	1050	47.11	2.86	1050	42.11	3.86
1250	49.97	1.35	1250	49.97	1.45	1250	45.97	2.52
1050	48.62	1.33	1050	48.52	1.18	1050	43.45	2.9
850	47.29	2.02	850	47.34	2.77	850	40.55	1.84
650	45.27	3.89	650	44.57	3.32	650	38.71	1.38
450	41.38	4.47	450	41.25	5.08	450	37.33	4.38
250	36.91	6.79	250	36.17	4.02	250	32.95	2.51
50	30.12	2.61	50	32.15	5	50	30.44	1.47

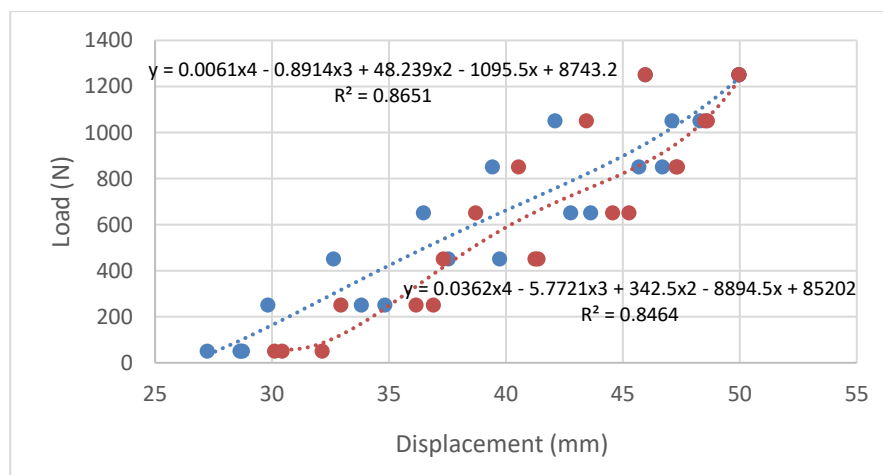


Fig. 4. Heel test graph results

The graph in Figure 4 displays the results of testing the performance of the prosthetic foot using the heel test method in accordance with AOPA standards. The test consists of two main phases, namely the loading phase and the unloading phase. The loading phase was indicated by the blue dot, and the unloading phase was indicated by the orange dot. The test results show a good correlation between the applied force and the deflection of the prosthetic

leg. This confirms the ability of the testing machine to see the mechanical properties quite accurately. The loading phase shows a polynomial trend with an R^2 value of 0.8651. This value indicates that this test model has a level of precision of 86.51%. Similarly, the unloading phase followed a polynomial trend with an R^2 value of 0.8464, suggesting a slightly greater precision (84.64%) in unloading behavior.

The energy absorption and return characteristics were analyzed by integrating the areas under the force-displacement curves using the trapezoid method. The mechanical testing machine successfully evaluated the force-displacement response, energy absorption, and energy dissipation of the Ottobock SACH foot. The energy absorbed during loading was 10.53 J, while the energy returned during unloading was 9.06 J, resulting in a hysteresis loss of 1.47 J. The results demonstrated that the prosthetic foot effectively absorbs and dissipates energy, with a hysteresis loss of 1.47 J (13.96%), consistent with expectations for a shock-absorbing prosthetic foot. The high R^2 values (0.8651 and 0.8464) indicate that the machine provides reliable and repeatable data. This value validates its effectiveness for prosthetic foot testing.

The Otto Bock SACH foot exhibited an energy return of 86.04%, which is below the AOPA threshold of 82% for dynamic heels. Although the return percentage is relatively high, the displacement criterion remains the limiting factor in classifying the foot as a dynamic heel. This result confirms that the Ottobock SACH foot prioritizes shock absorption and stability rather than energy return, aligning with findings from Geil [15] and Hafner *et al.* [14], who noted similar behavior in low-activity prosthetic feet with cushioned heel structures.

Figure 4 shows a clear picture of the performance of the prosthetic foot during the loading and unloading phases of the heel test. The relatively high R^2 values in both test phases indicate that the polynomial regression is quite effective in explaining the data, even though there is little difference between the loading and unloading phases. The prosthetic foot showed a strong ability to withstand loads with increasing force as the displacement increased in the loading phase. The prosthetic foot also showed a good ability to restore shape or energy when the load was removed in the unloading phase. Understanding these two phases is important to ensure that the prosthetic foot provides comfort and meets the performance standards set by AOPA. Previous literature has emphasized that the mechanical properties of the prosthetic foot, including hysteresis and energy return, greatly affect gait quality and patient satisfaction [13]–[17]. This study provides complementary evidence using standardized test equipment for the context of prosthetic development in Indonesia.

2. Keel Test

Keel testing generally covers several aspects such as strength, stability, durability, and flexibility. The strength property of a prosthetic measures how much load it can withstand before it breaks. Stability measures how well the keel maintains its shape and function under dynamic loads, such as walking or running. Durability measures how long the keel can be used without significant damage when used for a long time or in repeated load cycles. Flexibility measures the keel's ability to absorb and return energy during the gait cycle. The results of these tests are important to ensure that the prosthetic foot can be used safely, comfortably, and has a long enough service life. The results of the keel test can be seen in Table 4.

Table 4. Keel test data

Attempt 1			Attempt 2			Attempt 3		
Load (N)	Displacement (mm)	ΔD (mm)	Load (N)	Displacement (mm)	ΔD (mm)	Load (N)	Displacement (mm)	ΔD (mm)
50	82.44	4.96	50	81.78	4.69	50	82.06	5.53
250	87.4	1.43	250	86.47	1.31	250	87.59	1.54
450	88.83	3.38	450	87.78	3.66	450	89.13	2.34
650	92.21	3.16	650	91.44	3.12	650	91.47	3.28
850	95.37	2.07	850	94.56	1.85	850	94.75	4.1
1050	97.44	1.28	1050	96.41	1.54	1050	98.85	0.82
1250	98.72	2.27	1250	98.95	1.61	1250	99.67	3.65
1050	96.45	3.28	1050	96.34	2.49	1050	96.02	2.58
850	93.17	2.9	850	93.85	3.68	850	93.44	2.62
650	90.27	2.8	650	90.17	3.7	650	90.82	4.24
450	87.47	3.75	450	86.47	4.29	450	86.58	3.64
250	83.72	1.74	250	82.18	1.76	250	82.94	2.11
50	82.44	1.22	50	81.78	1.36	50	82.06	1.23

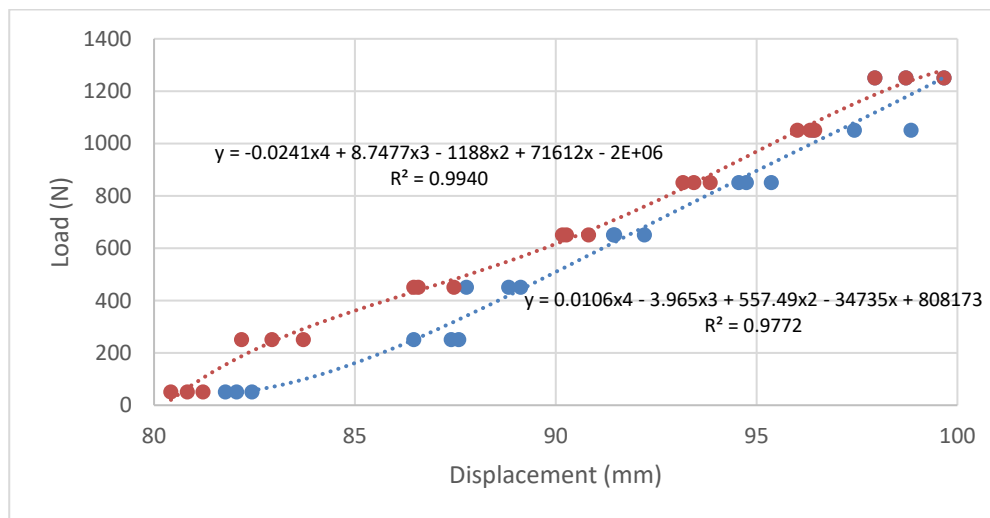


Fig. 5. Keel test graph results

The graph in Figure 5 illustrates the results of testing the performance of the prosthetic foot using the keel test method in accordance with AOPA standards. This test also involves two main phases, namely the loading and unloading phases, which are indicated by the blue and red data points on the graph. The loading phase, represented by the blue dots, shows how the prosthetic foot behaves when load is applied. The line representing the polynomial regression curve with an R-squared (R^2) value of 0.9942 indicates that 99.42% of the precision in the loading data is explained by this model. The unloading phase, represented by the red dots, illustrates how the prosthetic foot behaves when the load is gradually released. The red line representing the polynomial regression curve with an R-squared (R^2) value of 0.9772 indicates that 97.72% of the precision in the unloading data is explained by this model. Although slightly less precise than the loading phase, this value still indicates that the model is very good at describing the unloading behavior of the prosthetic foot. This result showed a strong correlation between applied force and displacement, confirming the ability of the testing machine to capture mechanical behavior accurately.

The results of the keel test were analyzed based on AOPA classification standards, which categorize prosthetic foot keels as rigid, flexible, or dynamic depending on their displacement at 1230 N of applied force and energy return efficiency. The test results of the Ottobock SACH prosthetic leg showed a deflection of 17.45 mm. This value is still below the threshold of 25 mm in the AOPA dynamic classification. However, the energy return value of 78.31% meets the standard. This is in accordance with the parameters of this leg as a prosthesis with a rigid keel (middle part of the foot). Generally optimized for stability and in accordance with previous biomechanical studies that highlight the comparison between stiffness and energy storage [16], [17]. Further analysis of energy absorption and hysteresis behavior using the same calculation method shows that 10.87 joules of energy are absorbed during the loading process and 8.93 joules are returned during the unloading process. This results in a hysteresis loss of 1.94 joules. This value is equivalent to a hysteresis percentage of 21.69%. This means that there is energy that enters and is lost due to internal damping and material deformation. This level of energy loss is consistent with the characteristics of a prosthetic leg constructed with a rigid keel and soft heel. This type of prosthetic foot generally prioritizes stability and comfort over dynamic energy return.

Womac *et al.* [16] also identified that energy storage components often sacrifice deflection values for better control and to reduce asymmetry in gait. In addition, the energy return efficiency of 78.31% meets the minimum requirements for a dynamic keel. The unmet deflection criteria in the Ottobock SACH prosthetic foot are best classified as a rigid keel prosthetic foot. These results confirm that the Ottobock SACH prosthetic foot is well suited for users who require high stability and controlled energy absorption. The rigid keel classification indicates that this foot is effective in providing stability and structural integrity while bearing loads. The softer heel properties ensure that the foot can absorb impact forces when the heel hits the ground and improve user comfort. The energy loss of 21.69% (hysteresis) indicates energy dissipation. This limits efficiency in high-performance applications such as sports or outdoor activities. The keel and heel test results confirm that the Ottobock SACH prosthetic foot meets AOPA standards for stability and shock absorption. This makes the Ottobock SACH suitable for users with low activity levels who prioritize comfort and safety. This prosthetic foot product does not fall into the dynamic keel or heel category. This means it is not optimized for users who require high energy return and propulsion when walking. This validates the ability of the mechanical testing machine to assess the performance of the prosthetic foot with sufficient accuracy. In addition, the test machine is able to pinpoint areas for improvement to further enhance efficiency and user experience.

IV. Conclusions

This study evaluated a mechanical testing machine for its ability to assess prosthetic foot performance. The Ottobock SACH foot was tested using AOPA classification standards, confirming it as a rigid keel prosthetic foot with a maximum displacement of 17.45 mm at 1230 N, below the 25 mm threshold for flexible or dynamic classification. While the 78.31% energy return efficiency meets the dynamic keel criteria, the displacement limitation confirms its design for stability rather than propulsion, making it ideal for low-activity users. The heel test further classified the foot as a cushioned heel, as its maximum displacement (9.87 mm) and energy return (72.5%) did not meet the dynamic heel requirements. Energy absorption analysis showed 10.87 J absorbed and 8.93 J returned, resulting in a hysteresis loss of 1.94 J (21.69%), consistent with designs prioritizing shock absorption over energy return. These findings are consistent with prior studies on prosthetic

foot performance, which reported that rigid keels with cushioned heels tend to dissipate more energy but offer higher ground contact stability.

The testing machine successfully captured force-displacement behavior, validating its accuracy in prosthetic foot assessment. As a further development to improve the mechanical testing machine, several upgrades can be made. It can implement integrating servo actuators for more precise load control and using high-resolution sensors for accurate force and displacement measurements would enhance the testing process. Expanding test conditions to include multi-axis loading can simulate real-world gait forces, while adjustable test fixtures would allow testing of various prosthetic foot sizes and configurations. This study provides analytical view that supports the development of local fabricating and forms the basis for the development of prosthetic testing standards in Indonesia. This research contributes to improving the quality of prosthetic foot that are safer, more reliable, and suited to user needs and encourages the growth of the national prosthetic industry.

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