Ergonomic Design of an Assistive Propulsion System for Manual Wheelchairs

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Abstract

Disability has always been a problem in developing countries like the Philippines. It is even aggravated by the environment and the lack of tools or equipment that can assist the handicapped people. Although there are equipment or assistive tools that designed specifically for use by these individuals, they contribute only a very small percentage of the total number of products that the handicapped people need. Survey was conducted to explore the current issues facing wheelchair users and to address the problems they experience in wheelchair usage. Results showed that users experience difficulty in propelling, steering, and transferring to and from the wheelchairs that result to discomfort and musculoskeletal disorders of the users. Thus, this research paper is focused on developing an ergonomic design of hand-cycle attachment that assists heavy-loaded wheelchair users especially when wheeling through long distances, challenging terrains and slopes. Features of the proposed design consist of synchronous propulsion system, foldability, mobility, adjustability, easy installation and stability by adding a stand that would keep the hand-cycle attachment in its upright position even when it is not in use. Clamping system and lever are also added to apply tensile and compressive forces to the wheelchair and can be rotated to maintain an ideal seat inclination of users in using wheelchairs. In addition to these, the design also includes a free-wheeling mechanism so the users will not have to apply force to the pedals all the time to keep the device running. The usability and effectiveness of the proposed hand-cycle attachment device was tested and validated using Rapid Upper Limb Assessment (RULA) tool. It was found that the use of the proposed device significantly decreased the risk of users for musculoskeletal disorders and provide ease and comfort for users compared to wheelchair use alone. Through the application of the principle of mechanics, propulsive force with the attachment device was computed to be significantly lower than the current tangential force applied by wheelchair users on the hand rims during propulsion. Respondents who tested the prototype also reported significantly lower propulsion difficulty scores.

Keywords
Assistive propulsion system, wheelchair users, hand cycle attachment, anthropometry, persons with disability (PWD)

1. Introduction

Disability has always been a problem in developing countries like the Philippines. The United Nations Development Program estimates that 80 percent of persons with disabilities live in developing countries. The Philippine Statistics Authority revealed that of the 92.1 million household population in the country, 1,443,000 persons or 1.57 percent have disabilities, with the second most prevalent of these mobility impairment (PSA, 2010). Not only is a great percentage (50%) of disabled people economically-challenged as shown by a survey conducted by the Philippine Institute for Development Studies (PIDS), but they are also deprived of doing many things that normal people enjoy. Disability, apart from being defined by a missing limb or an impairment of any of the five senses, is even aggravated by the environment and the lack of tools or equipment that can assist these handicapped people.

Although there are special products or assistive technologies that are designed specifically for use by these individuals, they constitute only a very small percentage of the total number of products that the physically challenged need to be able to use. Moreover, everyone, including the mobility impaired, need to be able to have access to a wide range of opportunities found outside, in the real world (AIES, 1994). On account of these facts, this study is geared towards the empowerment of Persons with Disabilities (PWDs), particularly the mobility impaired, in such a way that the solutions presented in this study will pave the way for PWDs to take control of their own mobility and live their lives as normally as possible. This study revolves around the exploration of the current issues facing wheelchair users and addressing the problems they experience in wheelchair usage.

The wheelchair is the most commonly used mobility device by people who cannot walk with their feet. This design works well with paved surfaces but is not ideal for rough and irregular terrains, as it has the tendency to tip over, and may have the difficulty of propulsion. The push rim tangential force exerted by wheelchair users ranges on average between 15 to 21 lb_f as stated in the study of Robertson (1996) concerning push rim forces and joint kinetics during wheelchair propulsion.

There are numerous studies and researches regarding the use of assistive tools and device for wheelchair users. One of which is the Commuter model designed by Freedom Technology in the Philippines (2006). The device resembles a big wheel toy with hand crank system that is used to propel the device in place of pedals. It can be used at higher speeds compared to ordinary wheelchairs, however, in order to use the device and propel its crank, the users should be in laying position that makes the user feel uncomfortable compared to ordinary wheelchair. Another device was designed by Life Elements (2009), that incorporates the parallel use of hand and foot force of users when propelling the device. It is similar to a tricycle with steering wheel through rack and pinion system operated by hand bars. The design is patterned from All Body Workout (ABW) trike proposed by Kerry McLean (2009) that also incorporates a hand and foot crank that simultaneously power the single rear wheel while steering. Another design was proposed by Holcomb et al., (2009) wherein the device uses asynchronous-pedaled hand cycle attachment instead of foot pedals and can be attached to a standard wheelchair. However, during the testing phase of the prototype, respondents found it difficult to attach the device as it required the use of the respondent's legs to support the weight, something not easily done by majority of the wheelchair users. Asynchronous hand-cycling is known to be more strenuous and less efficient than synchronous pedaling (Dallmeijer, 2005).

Previous studies have designed various mobility devices for wheelchair users focusing only on providing easier maneuverability and less physical strain without going through deliberate processes of determining the extent to which the need for such design exists and without determining the human factors in the design, resulting in products that are not completely user-centered. While there are many companies who design and manufacture hand cycles and machine-propelled tricycles in other countries, there are few that produce a product that is appropriate to the Filipino body size. To better address the concerns currently confronting PWDs in wheelchair propulsion, this study involves an in-depth analysis of the needs of wheelchair users and a thorough review of the current mobility aids that are available, resulting in the formulation of a new design with features that were found to be lacking in the existing mobility aids. Anthropometric measurements were taken directly from wheelchair users and PWDs' involvement in the design and testing phases was ensured to attain a customer-oriented product design.

2. Methodology

2.1. Data Gathering

The main respondents of the study are composed of 126 wheelchair users who are currently employed in Tahanang Walang Hagdanan in Cainta, Rizal, a non-stock, non-profit and non-government organization that provides livelihood, education and rehabilitation program for persons with disability. The researchers have conducted direct observation, surveys and interviews and actual measurements of wheelchair dimensions in order to assess the current design of wheelchair that will be used in the proposed hand-cycle attachment device in the study. Factors that will be considered in the design such as anthropometric measurement and body posture of users were also analyze using Rapid Upper Limb Assessment (RULA) in order to determine the risks for musculoskeletal disorders that will serve as the basis for researchers to develop a new device intended for wheelchair users.

2.2. Statistical Analysis

Data gathered from the surveys during the needs analysis and product testing underwent statistical treatment to facilitate deeper understanding about the respondents. Since the data gathered from the survey was qualitative, ordinal, and not normally-distributed, non-parametric tests are more appropriate to use. Gender comparisons as to the difficulties experienced in the propulsion, steering, transferring, and stopping the wheelchair were carried out by using the Mann-Whitney test, which is the non-parametric counterpart of a z-test. Factors affecting propulsion difficulties were identified through the Spearman's correlation test. On the other hand, Kruskal-Wallis test was used when more than two groups were being compared, such as the comparison of propulsion difficulties among the PWDs grouped according to the type of reason of their wheelchair-bound states. Statistical tests were also used in the data resulting from the survey for the prototype-testing. Comparison of the difficulties experienced by the users with and without the hand-cycle attachment was facilitated by the Wilcoxon Signed-Rank test, analogous to a Paired T-test, since there were two sets of measurements being compared that were taken from the same individuals. The Spearman's correlation test was again made use of in determining the factors affecting the experienced difficulties in propulsion.

2.3. Design Process

In order to come up with an ergonomic design of hand-cycle attachment for wheelchair users, the researchers made use of design tools such as product design and development, prototype making, value analysis and engineering, Kepner-Tregoe technique, Quality Function Deployment (QFD) and cost-benefit analysis. Using the design tools, the researchers have come up into a conclusion of designing an effective and efficient hand-cycle attachment for wheelchair users that will cater the needs and requirements of persons with disability.

3. Results and Discussion

The results of the survey showed that most of the respondents rated it very difficult to propel and steer the wheelchair and also find it extremely difficult to transfer to and from the wheelchair. However, they experience no difficulties in stopping the wheelchair whenever they wish to. Due to the aforementioned difficulties, they experience pains in the back, arms, hands, and shoulders.

It was also inferred using the Man-Whitney test that female wheelchair users experience more difficulty in propelling and transferring to or from their wheelchairs than men. Moreover, it was determined that there is no significant difference between the difficulties experienced by both genders in steering and stopping the wheelchair. It can also be noted that those who never experienced wheeling through distant places are mainly composed of PWDs who experience the greatest propulsion difficulty, while those who find it easier to propel the wheelchair are the ones who used their wheelchairs in travelling to considerably far places. PWDs whose reasons for being wheelchair-bound are neurological illnesses are having the most difficult experiences in wheelchair propulsion. Using Spearman's correlation test, factors affecting the difficulty of wheelchair propulsion were determined to be the age, the number of years being wheelchair-bound, and the medical condition of the respondent.

3.1. Rapid Upper Limb Assessment (RULA)

The assessment started with direct observations of the different wheelchair propulsion postures and interviews with the PWDs. The most difficult posture was determined to be the wheelchair user's position when starting to push the hand rims, as it is the posture when the wheelchair user exerts the greatest tangential force required to propel the wheelchair the evaluation focused on this posture. This assessment further proved the existence of the PWDs' need for immediate changes in their propulsion postures and served as a point of reference for the evaluation of the proposed solution that will later be discussed in this study. The proposed solution was geared towards the improvement of the user's posture when travelling from one place to another. The final score of 6 indicates that there exists a medium risk in the current posture, necessitating further investigation and immediate change in the posture. Efforts need to be put forth in the improvement of the wrist and arm postures, as these contributed largely to the high final score.

3.2. Quality Function Deployment

A set of survey questionnaires was distributed to the PWDs in order to know the customer ratings of each product characteristics that are deemed vital for addressing the customer needs. The list of the customer requirements as well as the mean ratings is shown in table below:

Table 1. Customer Requirements and Mean Ratings

Customer Requirements	Mean Rating
Comfortable	9.82
Low Cost	9.75

Durable	8.99
Propels fast	7.39
Lightweight	6.41
Safe	6.33
Foldable	6.14
Visually Appealing	5.30
Compact	5.08

The weights computed for each technical requirement served as indicators where efforts should be concentrated to ensure that the product is customer-oriented. Table 2 summarizes the initial design specifications derived from the House of Quality.

Table 2. Initial Design Specifications

Rank	Characteristic	Value	Unit	Tolerance
1	Type of material	Iron		Exact
2	Force it takes to propel	15	lb_f	Maximum
3	Weight	22	lbs.	Maximum
4	Force it takes to un/install	3.37	lb_f	Minimum
5	Amount of materials used	30	cu. in.	Maximum
6	Maximum working load	220	lbs.	Minimum
7	Young's modulus	10	Mpsi (million lb_f/in^2)	Minimum
8	Hand crank distance range	16.81-19.88	in.	± 2 inches
9	Braking force	270.0936	N	Minimum
10	Braking time	3	seconds	Maximum
11	Hand crank height range	38.7-41.2	in.	± 2 inches
12	Hand crank angle range	44.18-54.6	°	± 2°
13	Hand crank length	6.5	in.	± 2 inches
14	Force it takes to fold	3.37	lb_f	Minimum
15	Folded-state dimensions	2.75 x 2.75 x 4	ft.	Maximum
16	Wheel diameter	16	in.	Exact
17	Time it takes to un/install	60	seconds	Maximum
18	Density	0.33	lbs/in^3	Maximum
19	Service temperature	42.2	°C	Maximum
20	Corrosion rate	0.1	mm/yr	Maximum
21	Availability of material	Available in the Philippines		Exact

3.3. Value Analysis and Engineering

In this study, value analysis and engineering (VAE) was used to select the attachment method, propulsion method, folding system, and the type of material to be used. VAE began with the function analysis phase, followed by the alternative generation and alternative selection phase. Criteria used in evaluating the alternatives were taken from the House of Quality, as well as their weights. For each of the criteria, a rating system was established to quantify the value yielded by each alternative. Some design alternatives were from the literatures reviewed. The result of the analysis is shown in the table below.

Table 3. Design Concept Selection

	Criteria	Alternatives	Best Alternative
Propulsion System	• Force it takes to propel • Weight • Folded-state dimensions • Cost	• Standard hand crank • Synchronous propulsion system • Solar-powered system • Fuel cell-powered system	Synchronous propulsion system
Folding System	• Force it takes to fold • Weight • Folded-state dimensions • Cost	• Accordion System • Single-chain fold-over system • Two-chain fold-over system	Two-chain fold-over system
Material Type	• Service temperature • Corrosion rate • Density • Availability	• Steel • Aluminum • Titanium • Iron	Iron

	• Young's modulus • Cost		
Attachment Method	• Weight • Force it takes to install/uninstall • Time it takes to install/uninstall • Cost	• Slider • Vise grip • Master lock • Tower bolt mechanism	Tower bolt mechanism

3.4. Anthropometry

From the Quality Function Deployment, it was known through interactions with the respondents that their prime requirement above all product characteristics is comfort. Through the use of Anthropometry, the dimensions of the attachment were dictated by both the wheelchair dimensions and the body dimensions of the respondents of the study. The hand-cycle attachment was designed to be adjustable to accommodate 90% of the population. Anthropometric measurements were taken from wheelchair users in TWH. Aside from the ergonomic considerations specified in Table 4, the design was also aimed at improving the propulsion posture to lower the RULA score.

Table 4. Anthropometric Considerations

Design Considerations	Body Dimensions	Wheelchair /Hand Cycle Dimensions	Ergonomic Consideration
Range of Hand Crank Height	• Thigh Clearance (5^{th}-95^{th} percentile)	• Hand Crank Length • Seat Height	The hand crank should not hit the thighs during propulsion.
Range of Hand Crank Distance	• Thigh Clearance (5^{th}-95^{th} percentile) • Sitting Shoulder Height (5^{th}-95^{th} percentile) • Forearm Length (5^{th}-95^{th} percentile) • Upper Arm Length (5^{th}-95^{th} percentile)	• Hand Crank Length	The hand crank distance should not be too far that it requires the user to raise his trunk from the back rest and not too near that the chain touches the chest when the attachment is being installed.
Attachment Angle Range and Frame Length	• Foot size • Thigh Clearance (5^{th}-95^{th} percentile) • Sitting Shoulder Height (5^{th}-95^{th} percentile) • Forearm Length (5^{th}-95^{th} percentile) • Upper Arm Length (5^{th}-95^{th} percentile)	• Wheel radius • Hand Crank Height • Hand Crank Distance	The feet of the user should not make contact with the wheel when the hand-cycle attachment is installed.

3.5. Detailed Design

The figure below is a three-dimensional representation of the design of the device in its in-use state. The chains and sprockets were not modeled due to complexity.

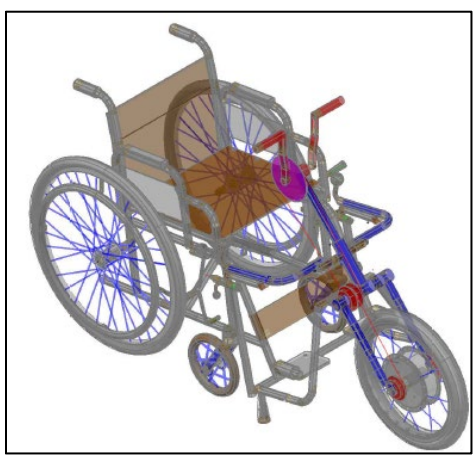

Figure 1. Prototype Model in its In-Use State

It took approximately ten days to fabricate the prototype, and several issues were encountered. Moreover, it also took a considerable amount of time to achieve the smooth locking mechanism, since there was a hard time aligning the attachment arm with the holder. Nevertheless, the desired working prototype was achieved as shown in figure below.

Figure 2. Working Prototype Design

3.6. Prototype Testing

Twenty wheelchair users participated in the testing phase of the product. The factors tested were the ability to propel through inclined pavements of slopes of gradient 1:12 or 4.8°, braking time, installation time, and steering. All the respondents were able to wheel through the inclined planes of 4.8°, and the braking time ranged from 0.89 to 2.46 seconds, which is within the design target. The time it took to install the attachment averaged 15.07 seconds, which is much faster than the target maximum time of 60 seconds. Hypothesis tests reveal that there is a significant difference between propulsion with and without using the hand-cycle attachment. People who find it slightly difficult to push the wheelchair now rated the hand-cycle as easy to propel. Most of them also find it easy to learn to install the attachment, as well as to install it without needing assistance from others. However, they rated braking slightly more difficult with the hand-cycle than without it because the hand brake was still hard to squeeze during the prototype testing. No significant difference was found between the steering difficulties experienced with and without the hand-cycle because the weight of the user and the wheelchair pulls the attachment down, making it hard to bring back the steering column to its normal position after being steered to the side. No substantial difference also existed between the difficulties experienced by both genders. A strong, negative relationship between the difficulty in propulsion and the sitting shoulder height, upper arm length, and forearm length was identified using the Spearman's correlation test. This signifies that those respondents who have shorter arms and lesser sitting shoulder heights experienced struggles in propelling the hand-cycle.

3.7. Prototype Evaluation

The prototype satisfactorily meets most of the specifications outlined in Table 4.2, which have been repeated here for convenience. Table 5 shows the initial design specifications and the current compliance.

Table 5. Prototype Evaluation

Characteristic	Target Specifications	Tolerance	Actual Specifications	Status
Type of material	Iron	Exact	Iron	Met
Force it takes to propel	15 lb_f	Maximum	3.8838 lb_f	Met
Weight	22 lbs.	Maximum	17.6 lbs.	Met
Amount of materials used	30 cu. in.	Maximum	17.6 lbs.	Met
Young's modulus	10 Mpsi	Minimum	11.6 Mpsi	Met
Hand crank distance range	16.81-19.88 in.	± 2 inches	19.5-23.3 in.	Not met
Braking time	3 seconds	Maximum	1.51 s	Met
Hand crank height range	38.7-41.2 in.	± 2 inches	35.53-41.53 in.	Met
Hand crank angle range	44.18-54.6 °	± 2°	37.81-65.88°	Met
Hand crank length	6.5 in.	± 2 inches	6.1 in.	Met
Folded-state dimensions	2.75 x 2.75 x 4 ft.	Maximum	2.17 x 1.17 x 3.67 ft.	Met

Wheel diameter	16 in.	Exact	20 in.	Not met
Time it takes to un/install	60 seconds	Maximum	15.07 s	Met

Characteristic	Target Specifications	Tolerance	Actual Specifications	Status
Density	0.33 lbs/in^3	Maximum	0.28	Met
Service temperature	42.2 °C	Maximum	168 °C	Met
Corrosion rate	0.1 mm/yr	Maximum	0.15 mm/yr	Not met
Availability of material	Available locally	Exact	Available in the region	Met

A. Hand Cycle Attachment Mechanics

The absence of a device that can directly measure the forces applied during propulsion prompted the application of the principles of mechanics in calculating for the force it takes to propel. The subsequent figure illustrates the force balance during cycling.

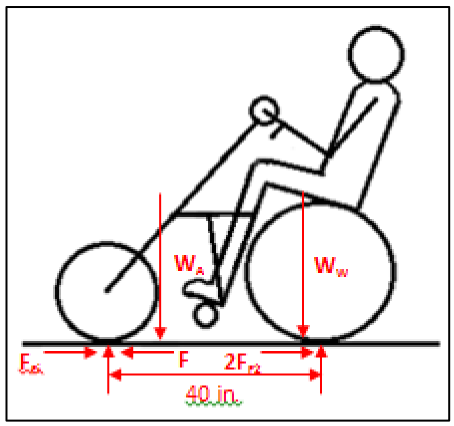

Figure 3. Force Balance during Cycling

The propulsive force F that drive wheels apply to the ground to move a vehicle along the path will determine the input force of the user when a torque analysis is carried out. Given the force F acting between the rear wheel and ground, the resulting force applied on the pedal can be calculated. Torque analysis can be performed based on the assumption that acceleration (linear and angular) is negligible. Hence, we can treat this as a uniform motion problem.

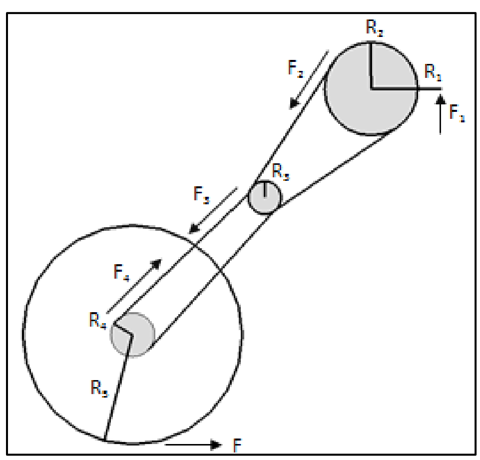

Figure 4. Torque Analysis

The required force on the hand crank was computed to be 3.8838 lb_f. This is significantly lower than the push rim tangential force ranging on average between 15 to 21 lb_f exerted by wheelchair users stated in the study of Robertson

(1996) concerning push rim forces and joint kinetics during wheelchair propulsion. Not only is this force easier to exert, but it also enables travelling longer distances for only a shorter period of time compared to a wheelchair's usual speed.

Compared with the previous wheelchair propulsion posture, the new posture eliminated the raising of the shoulders and the abduction of the upper arms. The lower arm is now situated at a lower angle in reference to the upper arm, and there is no need to move it out to the side of the body. Additionally, the wrist is also not bent from the midline. From a previous score of 6, the new RULA score of 3 now indicates a lower MSD risk level. This shows that the product indeed provides a more comfortable means of transportation for wheelchair users.

4. Conclusion

A vast majority of wheelchair users are faced daily with many struggles, attributable mostly to inaccessibility and the lack of the mobility required to participate fully in a normal Filipino life. Postures taken on by wheelchair users during propulsion pose a risk of developing musculoskeletal disorders as revealed by RULA. Additionally, wheelchair users perceive propulsion to be very difficult, resulting to pains in the back, arms, and hands. In response to these problems, this study revolved around creating a design of an ergonomic, detachable, foldable, and cost-effective hand-cycle attachment.

The prototype key specifications include a folded dimension of 2.17 x 1.17 x 3.67 cubic feet, a 15-second installation time, a gain ratio between the wheel and the hand cranks of about 3.48, a weight of 17.6 pounds, an adjustable hand-crank height and distance, and a material cost of PhP 4,527.44. Features differentiating the proposed design in this study from the existing mobility aids are the synchronous propulsion system, foldability, capability of being stowed inside vehicles, adjustability, easy installation, and stability by adding a stand that would keep the hand-cycle attachment in its upright position. A clamping system and a lever apply both tensile and compressive forces to the wheelchair, rotating it slightly by 10°, which was known to be the ideal seat inclination. These two product characteristics also facilitate the lifting of the caster wheels and the stand off the ground to prevent these from hitting slight bumps in the road during travel. Aside from these, the prototype also features a free-wheeling mechanism, so the user will not have to apply force to the pedals all of the time to keep the device running.

Quality Function Deployment gave way to the formulation of the initial design specifications that were given priority in the design. This tool also enabled the translation of the wheelchair users' needs and requirements into their technical equivalents. Through Value Engineering, it was decided upon which among the alternatives should be adopted for the propulsion system, folding system, attachment method, and the type of material that would yield the highest values as perceived by the customers. Working in conjunction with Anthropometric Analysis, the Theory of Inventive Problem Solving was used to address trade-offs identified in the roof of the House of Quality, thus resulting to the formulation of the design's adjustment mechanism. Design Failure Mode and Effects Analysis (DFMEA) was carried out to pro-actively prevent or mitigate the risks involved with the use of the product through some design modifications, maintenance procedures, and safety measures. The outcome was a working prototype that integrates all the technical requirements.

Issues experienced during the course of the prototype fabrication were the wheel diameter, corrosion rate of the material, and the hand crank distance range. The latter two, however, were resolved by coating the metal frame with paint and by placing a cushion at the backrest to retain the leaning position of the user during propulsion, respectively. The wheel diameter, although exceeding the specification, did not cause the weight of the entire attachment to go beyond the upper limit and in fact, also improved the mechanical advantage of the hand-cycle by increasing the distance travelled for every rotation of the hand crank. Still, most of the initial design specifications were adequately met.

Apart from the biomechanical analysis of the hand-cycle which showed that the required propulsive force indeed decreased, the prototype testing further built up on this finding by showing that users now perceive propulsion as an easy activity, compared to how they previously rated wheelchair propulsion as very difficult. The hand-cycle attachment was deployable in less than a minute, and users found it easy to install the device without needing assistance from other people. However, they experienced slight difficulties in steering the hand-cycle due to the weight being supported by the hand-cycle, and they also find it hard to squeeze the hand brake. RULA score decreased from 6 to 3, indicating that the risk of musculoskeletal disorders is much lower with the use of the hand-cycle attachment than the wheelchair alone.

Overall, responses from the wheelchair users who were the subjects of the study evidenced that the designed attachment device is an excellent solution to mobility problems of handicapped persons in the Philippines. Despite this, the design can still be subjected to more improvements and future work will enable this device to better address the needs of the PWDs.

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