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Design and Development of a Multifunctional Convertible Wheelchair in a Low-Income Country Context

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ABSTRACT

The objective of this study is to design and develop a mobility aid that performs three different functions to serve patients with a cost-effective space utilizing a wheelchair. The focus was to develop an affordable product considering the poor economic status of the targeted users. A convertible multifunctional wheelchair was developed that can be used as a stretcher and as a regular wheelchair, and it has a pair of crutches to assist in walking. The design and stress-strain analysis of the product was done using SolidWorks 2019. Then, the product was manufactured using the simplest available manufacturing tools and materials. It was possible to fabricate a prototype of this multifunctional at a very cheap cost of BDT 14,250 ($162 approximately). However, it is believed that in mass production, the unit cost can be reduced by 40-50%. The fabricated prototype was lightweight with an average weight of approximately 16 kg allowing it to be portable. The design specifications also ensure ergonomic comfort. It can be contended that this device can be a cost-effective solution for patients and public hospitals in Bangladesh and similar low-income countries.

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1. INTRODUCTION

A wheelchair is a wheeled mobility device designed especially for disabled individuals. The wheelchair is one of the most commonly used serviceable devices to promote potency and enhance the quality and independence of life for people who face trouble while walking. In addition to allowing mobility, a convenient and proper wheelchair satisfies the physical health and quality of life of the person using it by helping in minimizing some common problems such as pressure sores and improves

respiration and progression of deformities and digestion (Asia, 2010).

Wheelchairs are used by people for whom walking is difficult or impossible due to illness, injury, or disability. It is a necessity for them to use a wheelchair to move on their own. But when it comes to moving from the wheelchair, the patients need someone or something to hold on to or have support. There may be some situations that come up when they will need to move but find nothing to hold onto to stand or walk.

For ease of this problem, the authors came up with a novel idea of a multifunctional wheelchair that can serve the functions of a wheelchair along with a stretcher and a pair of crutches. The need for an extra wheelchair will be diminished as this product can serve the purpose of a wheelchair as well as a stretcher and a pair of crutches. This product can perform all these functions alone and need less space than other wheelchairs. By incorporating multiple functionalities in one single device, the proposed wheelchair is cost-efficient. The proposed multi-functional wheelchair is then a cost-effective device for the poor patients of Bangladesh.

This multifunctional wheelchair includes functions of wheelchair, stretcher, and clutches. There are three basic parts of the wheelchair, and these are the frame, the seat and the backrest, and the wheels. The seat and the backrest part will be of three rectangular sections where two of which will be used as seats. Each of them will be connected by a hinged mechanism so that they can be folded anytime. These rectangular parts will be connected to the frame by swing bar locks so that they can be removed as per need. The frame part will be used as crutches. So, it will have some foldable features. Some locking functions will be used here too. The armrest will be used as the crutch pad. Parts of the frame will be connected by folding and will make a pair of crutches. The rear wheel of the chair will have a removable feature when used as crutches. To use the wheelchair as a stretcher, there is no need to remove the wheel. In addition, it can boost the speed when used as a stretcher.

The structure of this paper is as follows: section 2 will review the existing literature to find out the research scope; section 3 will entail the methodological framework of this research; section 4 will propose the SolidWorks design of the proposed product; section 5 will show the stress-strain analysis of the design; section 6 will show the actual fabricated product; section 7 will be the results and discussion section; and finally section 8 concludes this work.

2. LITERATURE REVIEW

A literature review was conducted to understand the recent advances in the design and development of wheelchairs. Goher (2016) manufactured a wheelchair by which the client would have the option to change the stance of his chest area utilizing a customizable back help utilizing two direct actuators. This setup would permit the client to utilize the wheelchair as a versatile gadget just for recovery purposes without the need for outside help. The accessibility of sit-to-stand (STS) and back change systems would permit the client to do standard practicing which will upgrade blood courses as sitting for extensive stretches expands lower appendages' inability. Sunny et al. (2016) fabricated a wheelchair that could be used as a chair, a semi-chair, and a stretcher with the help of a lead screw associated with a pivot joint. The seat was removable so that human waste can be wiped out. A hydraulic jack was installed to lift the fundamental arm of the chair.

Hirudkar et al. (2017) developed a wheelchair cum stretcher that had the feature to transform into an electrical mobility aid when it comes to the staircase. It also had a detachable headrest while converting into a stretcher. The conversion was performed using hinges and a nut screw mechanism. Ghersi et al. (2018) proposed an idea of a Smart Medical Bed to aid patients who need care with inserted control capacities and intuitiveness. It had some regulatory frameworks enabling the caregivers with the ability to serve in a smarter way. The most important feature of this bed was that it would be used within a 60-meter perimeter of the hospital area with an installed navigation system.

Rui & Gao (2019) worked on a new multifunctional wheelchair with automatic postural adjustment designed to satisfy the user's nursing needs and reduce the workload of nursing staff. The kinetic characteristic curve obtained through kinematics analysis and simulation indicated that the process of wheelchair backrest reclining is smooth, and the rationality of the mechanism design is verified. Karpov et at. (2019) proposed software and hardware architecture for the robotic wheelchair and its multimodal user interface. This architecture supported several feedback types for the user including voice messages, screen output, as well as various light indications and tactile signals.

Sandoval-Bringas (2019) proposed multifunctional capacity to direct the chair, by means of the inclinations of the head detected in an accelerometer implanted in a headset, through voice commands, and through a mobile application developed for devices that had the Android operating system. Parthasarathy et al. (2020) designed and fabricated a wheelchair using Arduino UNO as a microcontroller allowing the product to recline using a digital accelerometer, an ultrasonic sensor to sense any obstacles in front of it, and two DC Motors to move using a thumb-controlled joystick.

Mohanavel et al. (2020) introduced a wheelchair cum stretcher using a hinge and nut screw Mechanism. Their product is a simplified version of a folding wheelchair enabling it to convert into a stretcher very easily. Lim & Ng (2021) conceptualized a foldable wheelchair stretcher by advancing its design and development procedures. The authors discussed the durability of the foldable wheelchair stretcher tested using stress and displacement analysis by applying twice heavier of the maximum load.

Cao et al. (2021) introduced a multifunctional wheelchair that consolidated its potency, gait training, and multi-posture transformation through voice, button, and mobile terminal control. The researchers analyzed functional requirements, mechanical structure, control system, and kinematic simulation of the wheelchair. Reddy et al. (2021) introduced an ergonomic, stairs climbing wheelchair with a swift and steady transversion character along with theoretical dynamic analysis on the motion of the wheelchair for transmissibility. Akhil et al. (2021) developed a wheelchair that was usable both indoors and outdoors, had the features to lift a patient directly from the bed, and could also be used as a walker. The authors used a screw nut mechanism as the working principle of the product and for moving purposes.

Shah et al. (2021) introduced a folding stretcher into a wheelchair from which the stretcher part could be detached from the main frame according to the user's convenience. The foldable feature enables less space utilization for a big number of

products, especially for places having space constraints. The transformation from wheelchair to stretcher could be performed using lever operation.

Very recently, Xiong et al. (2022) developed a multifunctional electric wheelchair with a rehabilitation training module. It had a leg structure for the user to form a crank-rocker mechanism. The rehabilitation module could be adjusted forward and backward or hidden under the wheelchair completely. The authors also used software to detect users' intentions. Meng et al. (2022) presented a smart wheelchair that had three postures, which are sitting, standing, and lying with a bionic shifting mechanism. It was defined and analyzed according to the requirements of a human body by biomechanical characteristics for position transformation. The design was simulated using Adams (Automatic Dynamic Analysis of Mechanical Systems) software.

After reviewing several research papers on relevant products, the proposed product was found to be unique and versatile. One of the reviewed products has a wheelchair feature that can be executed only indoors which is a limitation of this product. Another product needs a permanent attendant to aid the patient in using it whereas this product does not need any attendant unless the patient requires personal support. Another reviewed product has a navigation system installed that can operate within 60-meter perimeters of the center. Problems will arise if a patient needs to go further than 60 meters. In fact, 60 meters is a very short distance to cover. The authors find a product with a detachable headrest that is detached using a nut-screw mechanism. However, each time an attendee will be required to perform the job.

One of the reviewed products has a foldable feature that enables it to convert into a wheelchair, but the design was developed in such a way that no foamed/padded seat can be attached to provide comfort to the user. No product was found that has an automatic motor-controlled feature to perform the conversions. No other modified wheelchairs have the feature to utilize crutches as Armrests and the exempting mechanism of the crutches is also a unique one. Also, the average production cost of the existing products is way higher making them unaffordable for low-income people. That is why there is a research gap and there is a need for the development of multifunctional wheelchairs for low-income countries such as Bangladesh. Therefore, the objective of this research is to design and develop a low-cost multifunctional convertible wheelchair with a focus on low-income people. For the representative of low-income countries, the authors chose Bangladesh. This product alone will serve as three different products that too are easily convertible. This product will also have a removable bottle holder attached to the left armrest. The footrest will be movable, and the crutches will have flexible lengths.

3. METHODOLOGY

For this research, the research framework shown in **Figure 1** was followed. The research framework consists of the following steps:

Step 1 - Design of the wheelchair using SolidWorks: the design of the wheelchair has been done using SolidWorks 2019 (by Dassault Systèmes). Before doing the design, a customer survey was conducted to find out the customer requirements. The major requirements were found as follows: foldability, ease of operation, low cost, lightweight, ergonomic design, and multi-functionality.

Step 2 - Stress-strain analysis of the design: the necessary stress-strain and displacement analysis of the design has been carried out using SolidWorks 2019 (by Dassault Systèmes).

Step 3 - Selection of materials for wheelchair fabrication: to ensure a simple and systematic approach to making the right decisions for material selection, an analysis of parts and their stress has been carried out. Depending on the strength and weight of each part, the selection of materials for the fabrication of the product has been done as follows: stainless steel, aluminium alloy, rubber, and leather.

Step 4 - Selection of manufacturing processes for wheelchair fabrication: The operations and machines used to process all the parts of the product are – casting, drilling, tube bending, and roll milling.

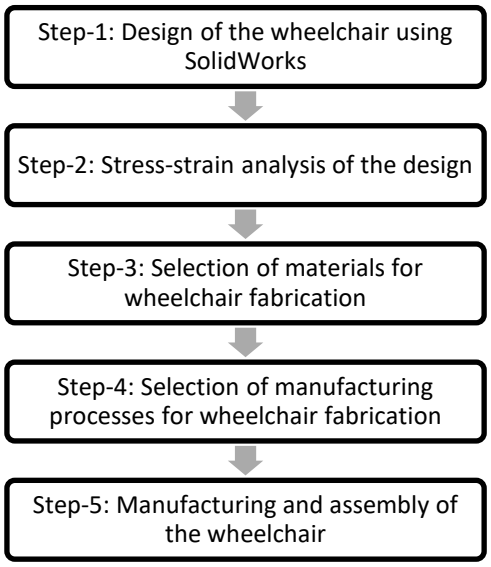

Figure 1. Research framework for this study

Step 5 - Manufacturing and assembly of the wheelchair: after manufacturing the product by parts, the assembly operations will be performed to get the final product.

4. SOLIDWORKS DESIGN OF THE WHEELCHAIR

An approximate design of the product is generated in this design process. The design of the product "Multipurpose Wheelchair" was done using SolidWorks 2019. The SolidWorks design of the product is shown in **Figures 2** to **4** which shows the wheelchair mode, fully expanded crutch, and stretcher mode, respectively.

5. STRESS-STRAIN ANALYSIS OF THE DESIGN

Stress analysis was conducted to determine the stresses in materials and structures subjected to forces. Stress analysis (Prasetiyo & Sekarjati, 2022) of “Multifunctional Wheelchair'' was done using SolidWorks 2019. All analyses were performed for an input load of 200 kg. The findings of the stress-strain and displacement analysis of the critical components of the design are discussed below.

Figure 2. Wheelchair mode

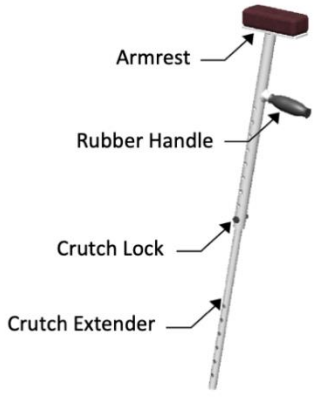

Figure 3. Fully expanded crutch

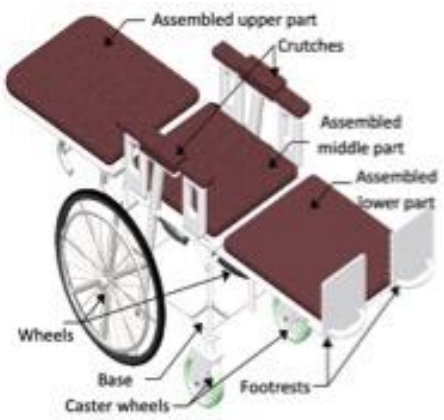

Figure 4. Stretcher mode

5.1 Assembled chair base

For the stress analysis of assembled chair base, which is made of mild steel, the yield strength (55.15 MPa) is 9 times the Von Misses stress obtained (6.364 MPa), indicating that the design is considerably safe (**Figure 5**).

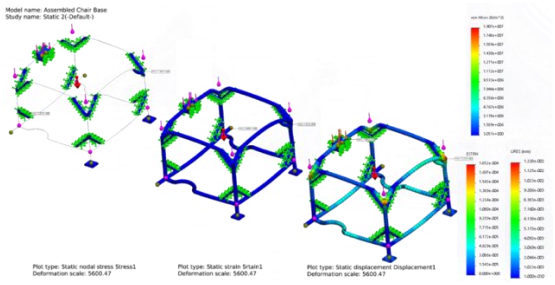

Figure 5. Stress-strain and displacement analysis of assembled chair base

5.2 Backbone key

For the stress analysis of the backbone key, which is made of mild steel, the yield strength (282.7 MPa) is 9 times the Von Misses stress obtained (29.58 MPa), indicating that the design is considerably safe (**Figure 6**).

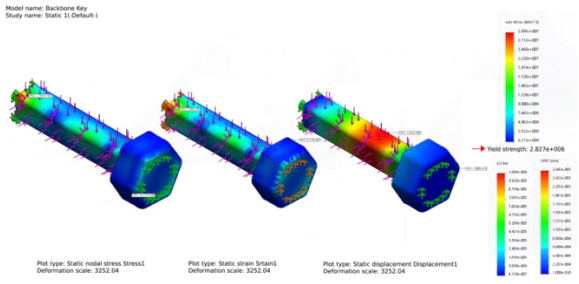

Figure 6: Stress- strain and displacement analysis of backbone key

5.3 Base connector

For the stress analysis of the base connector, which is made of mild steel, the yield strength (55.15 MPa) is 18,457 times the Von Misses stress obtained (2.988 kPa), indicating that the design is considerably safe (**Figure 7**).

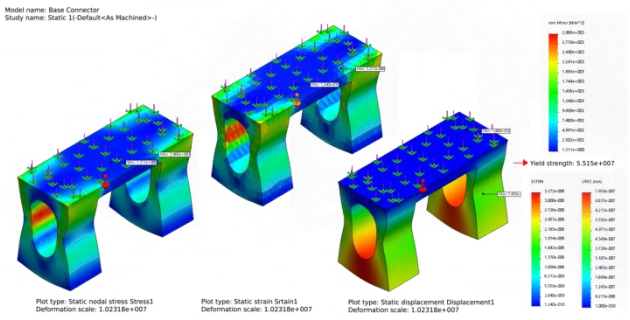

Figure 7. Stress- strain and displacement analysis of base connector

5.4 Caster wheel clip

For the stress analysis of the caster wheel clip, which is made of mild steel, the yield strength (55.15 MPa) is 19,043 times the Von Misses stress obtained (2.896 kPa), indicating that the design is considerably safe (**Figure 8**).

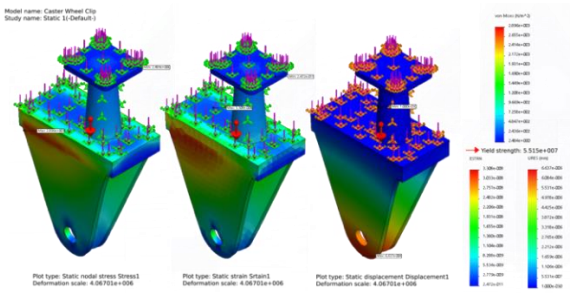

Figure 8. Stress-strain and displacement analysis of caster wheel clip

5.5 Wheel

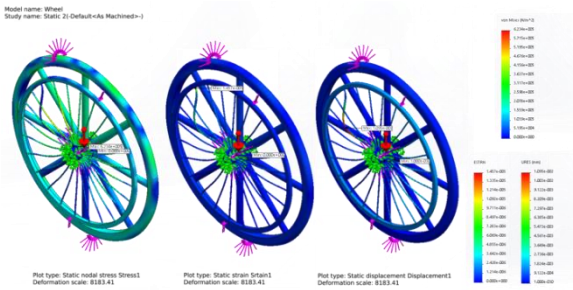

Figure 9. Stress- strain and displacement analysis of wheel

For the stress analysis of the wheel, the Von Misses stress obtained is 62.34 MPa, indicating that the design is considerably safe (**Figure 9**).

5.6 Hip rest frame

For the stress analysis of the blade, which is made of mild steel, the yield strength (551.5 MPa) is 903 times the Von Misses stress obtained (0.6106 MPa), indicating that the design is considerably safe (**Figure 10**).

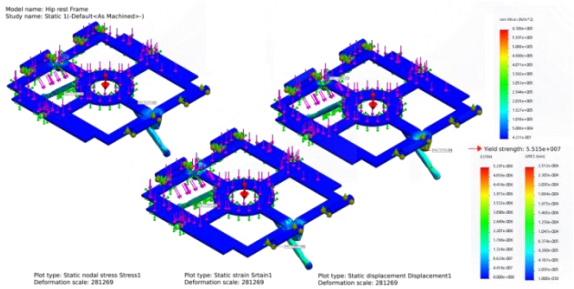

Figure 10. Stress- strain and displacement analysis of hip rest frame

6. ACTUAL FABRICATED WHEELCHAIR

The images of the actual fabricated product are shown in **Figures 11** to **13** which shows the wheelchair mode (fabricated), fully expanded crutch (fabricated), and stretcher mode (fabricated), respectively.

Figure 11. Wheelchair mode (fabricated)

Figure 12. Fully expanded crutch (fabricated)

Figure 13. Stretcher mode (fabricated)

7. RESULTS AND DISCUSSION

The fabrication of the product was done using the following manufacturing processes:

Casting: After being cast, the parts were all further machined and finished by using a shaper machine (cone pulley shaping machine, model: AG-30/ CPB 30) and grinding machine (manual surface grinding machine, model: M230) as per requirements.

Drilling: Some of the parts are processed using drilling operations. The drilling machine used was mild steel deep hole drilling machine, model: DHD-1000/2000.

Tube Bending: Chair base members are tube bent in specific places as per requirements.

Roll Milling: It is used to produce seamless pipes that were needed in different lengths and diameters mostly in the base connector and armrest structural parts. Some were also needed in different places on the chair. For this, a local manufacturer was contacted and asked to provide the pipes of the requirements. Roll milling operation was used to create pipes from billets.

Manufacturing and assembly of the wheelchair: At first, the structural members of type 1 (OD0.9 & ID0.6) are welded together to form the Chair Base. To give the structure additional support, structural members of type 2 (OD0.8 &

ID0.5) are welded between the 90 degrees contact points of each pair of Type 1 structural members. Then the base connector is welded to the base structure. The main wheel member is then inserted accordingly. The pairs of wheels and caster wheels are then attached to the base structure through mechanical fasteners (screws) and welding. The chair hand rests, crutch holsters, and female key parts are welded to the hip rest frame.

The female key part of 10.5 inches is to be welded at 4.76 inches from the the centre of hip rest frame and the female key part of 7.23 inches is to be welded at 6.65 inches from the centre of the hip rest frame. Rolled aluminum alloy bars are then fillet welded to the hip rest frame. Finally, the entire assembled hip rest frame is welded to the top of the chair base. The leather pads are now hot glued on the chair hand rests & hip rest frame.

Both types of straight & bended handle tubes are welded with the upper rest frame. An aluminum alloy bar is welded to the frame to make it lightweight (Rahardian et al., 2021). On it, the female key part of upper rest frame is welded in parallel direction with the surface. Finally, the assembled upper rest frame is then mounted with the hip rest frame through bed joint pin. The pin is now capped & only rotary movement is now available for the upper rest frame. Also, the leather pad is now hot glued on the upper rest frame.

With the Lower Rest Frame, the Feet Rest Pin Holder is welded on both sides. An Aluminum Alloy Bar is welded to the Lower Rest Frame, followed by the Female Key Part welded on it. The Feet Rests are then attached to the Lower Rest.

Cost analysis: The breakdown of the cost for producing the prototype is shown in **Table 1**.

Table 1. Cost estimation for producing the wheelchair prototype

Cost type	Cost per unit ($)
Raw material cost	$58
Purchased parts cost	$31
Machining cost	$18
Labor cost	$16
Manufacturing overhead cost	$24
Miscellaneous cost	$15
Total	$162

Technical specification of the product: The important technical specifications of the produced prototype are listed in **Table 2**.

Table 2. Technical specification for each part

Attribute	Specification
Back wheel diameter	22”
Front wheel diameter	9.5”
Average top height	44”
Average armrest height	32.5”
Seat dimension	22”x21”
Backrest dimension	24”x23.5”
Range of adjustable height of the crutch	30” to 42.25”
Weight of the product	16 kg

8. CONCLUSION

The fabricated multi-functional wheelchair is an effective mobility aid for disabled people without the requirement of any attendees. The objective was to develop an affordable, user-friendly, multi-functional, lightweight, and sustainable product. Support has been developed to help the stretcher mode remain horizontal. The inclination of the wheelchair was set after performing ergonomic research on a comfortable range of inclination. The crutches can be removed using the vertical upward rotational mechanism and can be inserted again using the downward motion. A pair of handles are attached to the backrest part for the ease of the attendee. The whole product is designed based on a cube-like frame which is manufactured using hollow stainless tubes. For the joints, the arc welding procedure was adopted. Utterly basic and simplest methods were used to keep this product affordable for the poor and low-income

people of Bangladesh. This device can also be used in government hospitals upon recommendation by the medical professionals.

The cost of production for this single unit of product was BDT 14,250 ($162 approximately). However, we believe that in mass production the unit cost can be reduced by 40-50%. The fabricated prototype was lightweight with a weight of approximately 16 kg, making it portable. This low-cost product could also be adopted in countries with similar economies like Bangladesh.

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