Development and Analysis of a PVC-based Standing Wheelchair using Finite Element Analysis

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Abstract: Natural calamities like earthquakes and man-made disasters like transportation accidents result in physical injuries and fatalities. Serious injuries can cause spinal cord damage and paraplegia. Paraplegia is a kind of motor disability characterized by the loss of control over one's lower extremities caused by neural damage to the lower spinal cord. Paraplegics have difficulties in their day-to-day activities, needing assistance from others to participate in society. Their quality of life is affected, not only from the effects of their disability, but also from the lack of available healthcare. The standing wheelchair aims to bring back the independence in mobility of the user by helping him to reach out objects placed in a high area. It would also facilitate therapeutic standing by allowing it to stand against gravity and prevent bone density loss. Polyvinyl chloride (PVC) pipes for the wheelchair structure to keep the frame lightweight, portable, and cost-effective, while capable of supporting the patient. The frame is specifically designed for a standing wheelchair powered by gas lift systems, which do not require an electrical power supply. All these materials are readily available in the market, therefore the production of this medical tool can be locally manufactured, thus resulting in affordable prices and better accessibility. Digital model for the structure is created using the CATIA. Through Finite Element Analysis, a 70kg load was applied on the seat which simulates the average weight of a person. Trials were done in three positions—sitting, semi-standing, and full standing. Only minimal deformation was seen in all positions. The PVC pipes are determined as an alternative material for the structure for a standing wheelchair.

Key Words: paraplegia; standing wheelchair; assistive device; gas lift; finite element analysis

1. INTRODUCTION

Disability disrupts the day-to-day activities of a person and obstructs the connection between the person and their society and environment. Fifteen percent of the world's population are disabled, with 110 million to 190 million adults having difficulty functioning in day-to-day activities, and the rate of disability continues to increase as life expectancy rates increase each year (World Health Organization [WHO], 2018). Among all types of disability, however, physical and motor disability, including paraplegia, can be considered as one of the most debilitating types of disability, leading to financial, emotional, and mental problems. In the Philippine setting, specifically, the disability rates are increasing rapidly, from 637,000 disabled to 942,000 disabled in 10 years (Philippine Statistics Authority, 2018).

Paraplegia is a type of motor disability that affects the lower extremities of a person due to an injury of thoracic, lumbar, and sacral spinal cord segments caused by neurological trauma (Nas et al., 2015). It not only disrupts the day-to-day function of the paraplegic, but also significantly affects their quality of life, causing chronic pain and diseases. Paraplegia can cause sensory loss, urinary and anal sphincter dysfunction, fractures, and orthostatic hypotension (WHO, 2018). Data from the study conducted by Hughes et al. (2017) shows that paraplegics have issues with pain, independence, mobility, relationships, hygiene, emotion, home environment, and identity. This data indicates that paraplegia affects the emotional and mental wellbeing of a person. Moreover, paraplegia impairs patients, hindering their connection to social and community participation (Nas et al., 2015).

These problems are usually addressed with therapy sessions, supporting muscle strength and restoring paraplegics to the highest level of function. Furthermore, the use of standing devices, such as a standing wheelchair, plays an important role in the rehabilitation process of paraplegics (Dicianno et al., 2016). Using a wheelchair as a tool for therapy for paraplegia could be helpful, especially when the staffing of rehabilitation centers is thinned out with the rising number of disabled people. Vorster et al. (2019) explains in their study that patients with paraplegia-like muscle dystrophy were able to improve the movement capability and emotional wellbeing of the patients. Those affected by paraplegia will eventually have to adapt to daily living, such as executing simple tasks like showering, or reaching for an object on a high shelf. A standing wheelchair can bridge a gap between the paraplegic and those activities, while providing outpatient therapy. Standing wheelchairs can assist paraplegics in the workplace, such as nurses, store clerks, or teachers, who need to sit and stand throughout the day.

However, the availability and accessibility of these wheelchairs are limited. Motorized standing wheelchairs can be priced from $18,000 to $55,000, depending on the features (Wechsler, 2020). Additionally, the materials and electric motors employed in the standing wheelchair designs could be costly. These problems can be mitigated through inexpensive and strong materials like the gas lift modules and the PVC pipes.

In order to address this problem and provide better healthcare devices in the Philippines, the proponents aimed to develop a cost-effective standing wheelchair using PVC pipes that will be powered by gas lift modules to assist the user in standing. The study focused on the structural design of the wheelchair. The wheelchair structure was digitally designed and tested through a CAD software called CATIA. This model is limited to a person weighing 70 kg to 80 kg, and will not use electricity, as the gas lift will be utilized for transformation.

2. METHODOLOGY

2.1 Wheelchair Design

The standing wheelchair will function as the paraplegic's lower extremities, so it is of utmost importance to consider the structure, function, and ergonomics of the wheelchair, even addressing some current problems of the standard wheelchair. In Desai et al. (2018), it is stated that some physical and psychological problems manifest with static activity in wheelchairs, such as fatigue, pressure sores, excretion failure, and urinary calculi. These problems can be solved through proper design and ergonomic considerations. Desai et al. (2018) modeled the wheelchair using hollow pipes , stating that hollow pipes have a better weight to strength ratio. Hence, the hollow pipes are relatively durable and lightweight.

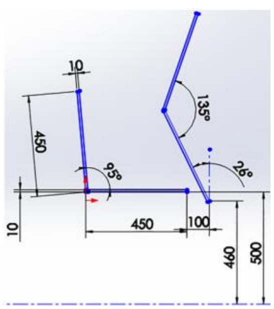

Fig. 1 Angles and measurements in mm of the transformation states in standing and sitting position.

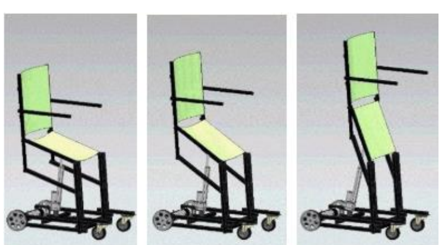

Fig. 2. The Robotic Mobilization Device

TABLE I. DIMENSIONS OF STANDARD WHEELCHAIR IN IS 7454:1991

Sr. no.	Dimensions	Size in mm
1	Overall length	1000-1100
2	Overall width	650-720
3	Overall height	910-950
4	Seat height from floor at the front	480-510
5	Slope of the seat	10-30
6	Slope of backrest with respect to floor	50-70
7	Distance between seat and footrest	400-450
8	Armrest height from seat	220-230
9	Seat depth	420-440
10	Clearance of footrest from floor	90-200
11	Clearance of frame from floor	90-110
12	Wheel diameter	609.6 (24")
13	Weight of the wheelchair	25kg max

TABLE II. DIMENSIONS OF THE STANDING WHEELCHAIR DIGITAL MODEL

Sr. no.	Dimensions	Size in mm
1	Overall height	700-1290
2	Overall width	420
3	Seat height from floor at the front	540
4	Seat length	450

The dimensions of a standard wheelchair shown in Table 1, taken from Desai et al. (2018), serve as guides in designing a standing wheelchair. The dimensions of the digitally modeled standing wheelchair product are shown in Table 2. Additionally, the angles illustrated in Figure 1, taken from Desai et al. (2018), are considered for wheelchair transformation. Modifications from the design of Desai were done to incorporate a gas lift. The phases of the wheelchair transition are demonstrated in Figure 2, taken from Panchal (2019). The seat is rotating due to the torque produced by the gas lift. The linking mechanism below the seat maintains the backrest at a constant angle relative to the ground throughout the transition. Using gas lifts, the proponents can replicate the standing mechanism of electric-powered wheelchairs with ideally minimal costs. As devices that use pneumatic power from compressed air, gas lifts are capable of high force outputs even when in small modules (Padmanabhan et al., 2014). Furthermore, gas lifts do not require an external power source because their energy comes from the stored compressed air. The wheelchair frame was simulated to be built from 1-inch PVC pipes. Tee connectors, 90° connectors, and couplings, as well as PVC cement, were not simulated in the frame, but were implied. Transformation mechanisms, such as hinges, were also implied.

2.2 Structural Analysis

CATIA software was used in order to simulate the stress points of the wheelchair. Three digital models, with standard wheelchair dimension, were configured in three positions: sitting, semi-standing, and full standing. Point of maximum stress was observed in each position. The standing wheelchair comprises the following different parts such as seat, backrest, base, transform mechanism, pneumatic lift, and wheels. However, the structural analysis is limited to the frame and gas lift because these are the crucial components. Other accessory parts, such as cushion and armrest, are not included in the model. The wheelchair frame, consisting of the seat, backrest, and base was created as a single product in CATIA. Then, the gas lift was attached to the frame, in order to assess the structural integrity of the frame. During the static analysis, a constant force was applied to the area where the wheelchair comes in contact with the patient which is the seat and backrest, while all the parts are set as fixed.

The Finite Element Method was utilized to perform the static analysis in CATIA for assessing structural response due to stress (Chakrabarty et al., 2016). The stress points and displacements caused by an applied force was determined. During the analysis, the geometry of the problem is divided. Dividing the object being tested into more elements and implementing a higher order polynomial for computation yields a more accurate result.

3. RESULTS AND DISCUSSION

3.1 CATIA Model

The CATIA model simulated the structure and transformation of the wheelchair, as well as the stress points during the transformation. The figure above shows three digital models differing by position during transformation. They do not vary from each other when it comes to material or the measurement of the parts. These models are made to simulate the three phases—sitting, semi-standing or middle, and full standing—which are most likely to be subjected to maximum stress in the transformation from sitting to standing. The seat in the sitting phase makes an approximately 90° angle with respect to the backrest. In the semi-standing phase, the seat makes a 120° angle, while in the standing phase, the seat makes a 150° angle, both with respect to the backrest in the full standing phase.

Since the wheelchair frame and the gas lift are two separate parts in CATIA, coincidence constraints are set to mount the gas lift to the frame. The material for the frame is defined as PVC. For the gas lift, the material is defined as steel. The default material properties in CATIA library are used for both PVC and steel. These properties are shown below in table 3.

TABLE III. MATERIAL PROPERTIES

Physical Property	PVC	Steel
Density	1400 kg/m^3	7860 kg/m^3
Young Modulus	3x10^9 N/m^2	2x10^{11} N/m^2
Yield Strength	0.2 N/m^2	2.5x10^8 N/m^2

3.2 Finite Element Analysis

The digital models of the standing wheelchair have clamps located at the base and distributed forces on the seat and backrest. The fastening connection is established between the wheelchair and the gas lift. The clamps are to hold the wheelchair in place. The magnitude of the downward distributed force applied to the seat is 686 Newtons, which is approximately the average human weight of 70 kg. A small portion of the force, 25 Newtons, is applied to the backrest. In the finite element analysis, parabolic polynomial elements are used. The distance of the finite elements is 0.7 cm in full standing phase and 0.9 cm in sitting and semi-standing phase. The global error rates of all the analyses are less than 10%.

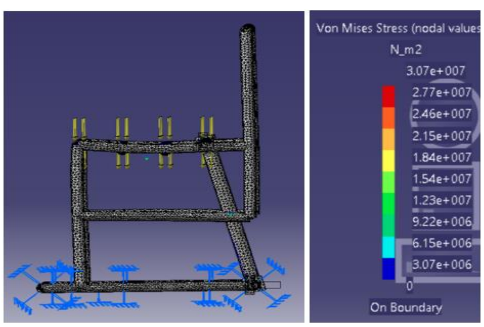

Fig 3. Von Mises Stress and bending in sitting phase

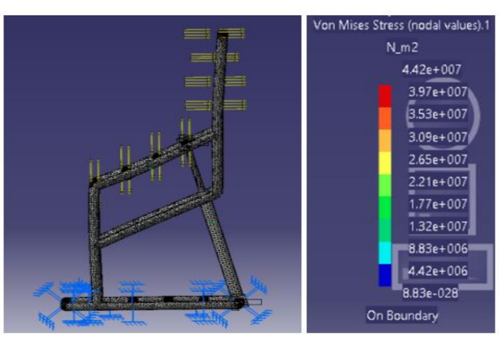

Fig 4. Von Mises Stress and bending in semi-standing phase

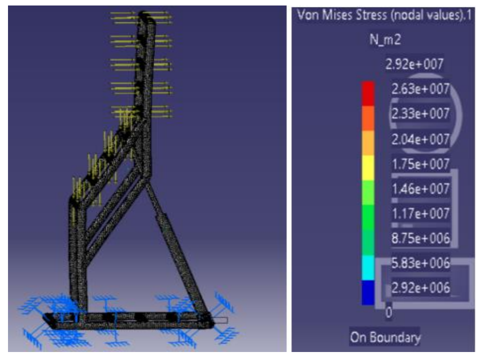

Fig 5. Von Mises Stress and bending in full standing phase

The Von Mises Stresses of each phase are shown in figures 3 to 5. The Von Mises Stress Values for the PVC pipe structures are almost 0, as indicated by the gray color. Compared to the yield strength of PVC, which is 0.2 N/m2, the PVC frame can withstand the stress. In the sitting phase, the majority of the wheelchair frame is subjected to relatively low amounts of stress, except for the area where the gas lift is connected. For the semi-standing and full standing phase, the stress point is located at the area of the gas lift. However, in all three phases, the majority of the wheelchair frame received relatively low stress. The bending of the wheelchair frame in each phase is also shown in figures 3 to 5. During the simulation, the seat is the most bent part in the sitting phase. In the semi-standing and full standing phase, the legs are slightly bent, implying that the structure can withstand the applied stress, while the bent parts require additional support when subjected to a much larger weight.

4. CONCLUSIONS

The construction of a PVC-based standing wheelchair is feasible because it can sustain the weight of an average person without compromising its structural integrity regardless of slight bending. Through Finite Element Analysis, it was demonstrated and supported that though there is minimal bending of the PVC pipes, they can withstand the stresses throughout the structure. Therefore, a PVC-based wheelchair is a potential alternative to conventional aluminum and steel wheelchairs. Further study on the kinematic analysis and the integration of pneumatic lift is recommended to improve the study.

5. ACKNOWLEDGMENTS

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