Chapter

Development of an Intelligent Standing Wheelchair with Reclining Characteristics

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Abstract

The widespread of motor neurone weakness has become a major concern as a result of accidents, ageing, birth defects and other hereditary diseases. A huge number of paraplegics can barely do activities for themselves without assistance from helpers. This study seeks to develop an intelligent wheelchair that has an assistive lifting and multi-posture reclining mechanisms to help in elevating the user from sit to stand posture as well as recline the seat for angles between 90 and 180 degrees through use of hydraulic linear actuators. The design would incorporate strain gauge sensors on the lower back area of the seat to enable the user to stand by merely leaning forward; thereby decreasing the strain on the lower back seat to trigger the lift mechanism until the required height is attained. While pressing the sit button on the console would enable the lowering of the user to a sitting position. The wheelchair development would also enable intelligent mobility through use of ultrasonic sensors to detect obstacles and assist in the braking effort by the user. An economic analysis was done to assess the feasibility viability of the design for local production. Some user requirement validation was undertaken to establish the extent to which the design would satisfy the key requirements of the intended beneficiaries.

Keywords: paraplegics, sit to stand, multi-posture reclining, intelligent, hydraulic linear actuators, strain gauge sensor, stress sensor, ultrasonic sensors

1. Introduction

An estimated 15% of the global population experience significant physical challenges [1] which affect the lower limbs and thus make mobility problems for this group of people. Assistive mobility technologies have been invented to aid the physically challenged people in moving from one point to another and these include wheelchairs, lifting aids, exoskeletons, walking devices and other devices [2]. However, in most cases, the user requires assistance in operating the device including help in pushing the wheelchair, support in using the bathroom, assistance in getting off the wheelchair etc. People using wheelchairs are exposed to secondary diseases associated with being sedentary. It was established that people with disabilities are more prone to coronary diseases and other related secondary diseases associated with lack of exercises and sedentariness. Effects on patients also include physical and psychological factors due to the prolonged seated posture [3]. With only a few caregivers, there is great need for improved assistive devices to give more independence to the physically challenged. It is in this regard that this study to develop an artificially intelligent wheelchair to assists users in reclining and getting up to standing posture and seat with reduced effort. Thus, it would aid the users to perform more tasks such as standing, maintaining eye to eye contact during conversations, cooking, exercising/physiotherapy, and reaching a top shelf among other activities.

2. Modern wheelchair review

With differing levels and causes of mobility impairment, this calls for upgraded wheel chair functions that can assist the users in performing standard tasks independently while minimising risk of contracting secondary diseases to the users. There is an increasing need for intelligent wheelchairs to elevate the user from seated to standing posture and vice versa as well as providing better flexibility of the user through improved manoeuvrability and increasing number of degrees of freedom (DoF) in terms of inclination of the chair.

Reclining wheelchairs: Also known as tilt-in-space wheelchairs, have seating platforms that can be tilted through various angles as shown in **Figure 1**. It allows the user to relax through different posture angles allowing blood flow to the lower limbs.

Manually operated standing wheelchair: The wheelchair uses bicycle chains to transfer power from tank tread-like push bars to the wheels or the system that lifts the user. It consists of a unique hand drive mechanism that allows users to drive the wheels of the wheelchair while seated, standing or in the range of positions in between (**Figure 2**).

Smart wheelchair: This typically consists of either a standard power wheelchair to which a computer and some sensors have been added or a mobile robot base to which a seat has been attached. Smart wheelchairs have been designed to provide navigation assistance to the user in a number of different ways, such as assuring collision-free travel, aiding the performance of specific tasks (e.g. passing through doorways), and autonomously transporting the user between locations. To avoid

Figure 1.
Reclining wheelchair [4].

Figure 2.
Manually operated standing wheelchair [5].

Figure 3.
Electric powered standing wheelchair [7].

obstacles, smart wheelchairs need sensors to perceive their surroundings. Proximity sensors are normally used to detect obstacles in the pathway of the wheelchair.

Powered standing wheelchair: This consists of an electric motor drive system powered by DC batteries mounted at the base of the frame. The speed of these motors is controlled by the remote control system to allow for forward, reverse and sideways propulsion of the wheelchair. On lifting the user, linear actuators and revolute motors (mounted at the back of the chair) are used to produce the required torque or control input signal from the remote control system to transform the shape of the wheelchair frame from seated to standing posture and vice versa [6]. The user is extended from a sitting position to a full standing position. The user's legs are locked and support the weight of the body at full extension. A hydraulic lift is used to complete the motion with elevation times ranging from 3 to 60 seconds (**Figure 3**).

2.1 Contemporary imitations of existing wheelchair designs

Most current designs use lots of expensive material and components, and this makes them unaffordable to the majority of the people who need them especially for communities in impoverished developing regions of the world. The wheelchair design in **Figure 3** requires the user to have legs that meet a minimum bone density to undergo this motion. Hence there is need for a design to accommodate all types of users with or without legs.

3. Materials and methods

The researchers conducted interviews with wheelchair users from local communities as well as visiting some patients at local health facilities such as Baines Physiotherapy & Rehabilitation Centre. The researchers managed to interpret the raw data in terms of customer needs and expectations into technical aspects thus helping in narrowing down the areas that needed improvement as per user needs as given in **Table 1**.

A network of contacts was developed to provide insight and guidance to refine the design output. These included members of the medical rehabilitation field, medical equipment suppliers as well as ergonomics and human motion experts in the field of physiotherapy.

In order to come up with the design mechanism for lifting the user from Sit to Stand (STS) and vice versa, it was crucial for the researchers to undertake a study in to the kinematics of standing up and sitting down from a chair. The next step was to analyse the joint movements (of the angles, knees and hips) for an individual as they stood up from a chair. It was important to follow this procedure (bio-mimicking human movements) so that the design would offer smooth operation as a physically unchallenged person.

Measurements of the individual formed the basis for determining wheelchair frame size, the need for adjustable ranges in component parts, and the need for customization to meet special needs. This was key in sizing the wheelchair for an

Wheelchair User Need	Technical Interpretation
Independence in operation	Automation & Intelligence
Multiple uses	Mechanisms (standing and reclining)
Balance	Safety and stability
Less cost	Economic
Comfortable ride	Suspension system and change of material
Adjustable	Functionality
Improved back rest design	Ergonomic design

Table 1.
Interpretation of user need.

average adult person. Appropriate size determinations of the wheelchair frame, seat, back, leg rests, and armrests based on measurements with an average bodied adult in an optimally seated position were taken and these built the foundation of the wheelchair design.

Three possible design concepts were generated, and the best option was selected using the Binary Dominance Matrix as the ideas were evaluated against the research objectives. Detailed engineering drawing designs were done using Solid Works and AutoCAD software. Special attention was also given to the actuation and sensory systems that were assembled in synergy to give the wheelchair autonomous and intelligent abilities.

The simulation process was carried out for both seated and standing postures. Calculations were done on the design to analyse it on the bending and torsional stresses acting on the components of the wheelchair under load in operation including deformation of stressed parts. The safety factor was obtained from these calculations and was compared against the standard safety factor. The researchers carried out the economic analysis to determine the costs of the parts and this was drafted in the Bill of Quantities to get the total cost of the components and their quantities.

4. Detailed design development

Table 2 gives the technical specifications of the intended wheel chair design.

4.1 Linear actuator and recliner concept

From the data gathered, the researchers came up with three possible solutions that were mainly different in the lift actuation mechanisms. Most of the attention of the drawings was paid to the working principle behind the lifting mechanism with the pros and cons for each concept discussed.

From the Binary Dominance Matrix (BDM), the concept on the Hydraulic Linear Actuator Lift and Recliner Mechanism (**Figure 4**) proved to be the optimal solution for the research design and was the most aligned with the requirements.

Eight selection criteria were considered and weighted for each of the design concepts; and each conceptual design was evaluated and scaled against a factor. The concept with the highest rating was considered the optimal solution for the design. The criterion factors considered included:

A. Ergonomics
B. Safety
C. Cost
D. Function
E. Simplicity of Mechanisms
F. Efficiency
G. Ease of Maintenance
H. Reliability

Figure 5 shows how the components that make up the mechanism are linked.

4.2 Linear actuator lift and recliner concept working principle

The mechanism consists of hydraulic linear actuators as the main source of power for the lifting and reclining mechanisms. When the command to lift the user is input, the battery powers the main hydraulic linear actuator to extend, pushing the wheelchair seat at an angle to the vertical. During this action, the

Specification	Measurement
Dimensions in mm	
1. Total Height (in seated posture)	1 200 mm
2. Total Height (in standing posture)	1 700 mm
3. Total length	1 280 mm
4. Armrest Height	$0 \leq h \leq 500\ mm$
5. Backrest tilt angle	90° – 180°
6. Seat Width	650 mm
7. Front Wheels	300 mm
8. Rear Wheels	600 mm
9. Footrest width	30 mm
Weights in kg	
10. Total Weight of chair	90 kg
11. Max User Weight	80 kg
12. Max Allowable Load	800 N
Features	
13. Power Source	24 V, 40 Ah
14. Max Driving Range with 40 Ah battery	30 km
15. Max Driving Speed	4.2 m/s
16. Max Safe Slope	15°
17.	

Table 2.
Technical specifications.

Figure 4.
Wheelchair in seated and standing posture showing max change in height $\Delta H_{max} = 0.5\,m$.

other actuators extend outwards and apply an upward force on the seat through the sliding assembly. The action of these actuators results in a resultant upward lift force that elevates and sustains the weight of the user as illustrated by **Figure 6** below.

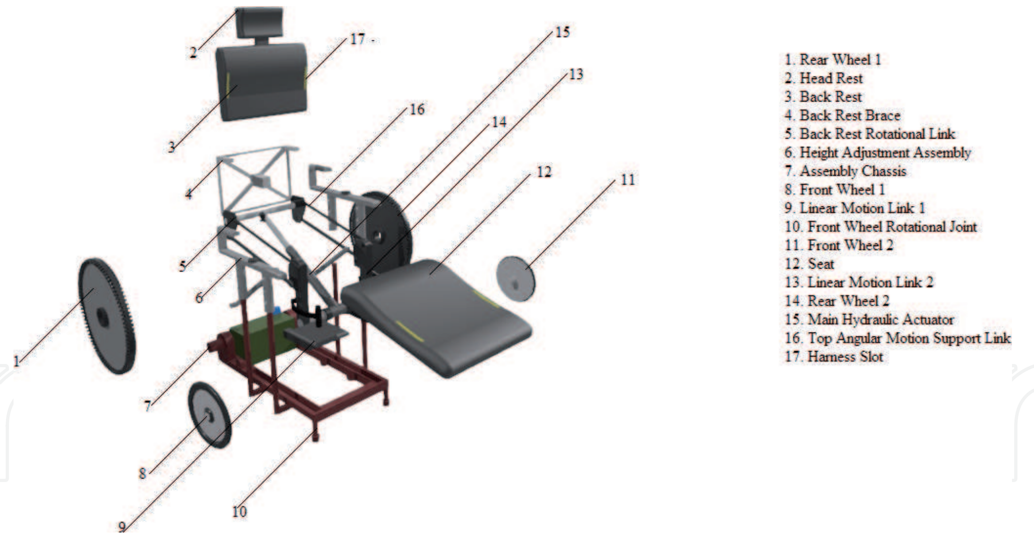

Figure 5.
Chosen concept exploded view.

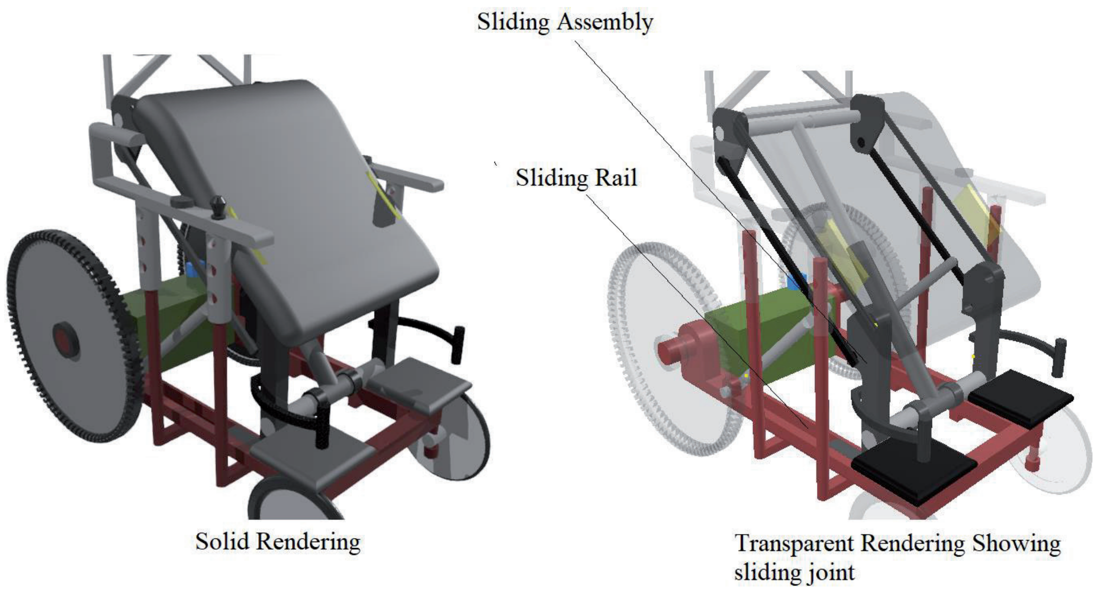

Figure 6.
Sliding joint mechanism providing lift for wheelchair.

The linear actuators used in this concept provide a smooth and stable movement of the wheelchair without delay, during height adjustment. The mechanism provides the possibility to design a better user control method for the convenience of most wheelchair users. However, application of this mechanism results in a relatively higher costs as costs of the linear actuators is higher as well as the other features that accompany it including power sources (batteries) (**Table 3**).

4.3 Autonomous drive control systems

The optimal design will consist of sensors and controls that to help in making it intelligent and providing autonomy. The wheelchair is driven by electronic speed differential motors that are directly coupled to the rear wheels of the chair. These motors provide the required torque for each wheel they are coupled to, and allow for different wheel speeds. This allows the motors to steer the wheelchair sideways when it is turning. The motors are powered by a 12 V lead acid battery connected to an Arduino microcontroller that receives input from the sensors and the joystick.

Wheelchair Operation	Left Rear Wheel	Right Rear Wheel	Wheel Speed V_W
Turn Left	Turns Backwards	Turns forward	$V_L < V_R$
Turn Right	Turns forward	Turns Backwards	$V_L > V_R$
Drive Forward	Turns forward	Turns forward	$V_L = V_R$
Reverse Drive	Turns Backwards	Turns Backwards	$V_L = V_R$
Brake/Stop	Stops	Stops	$V_L = V_R = 0$

Table 3.
Wheelchair controls.

The microcontroller is the central processing unit of the wheelchair. It receives input and gives commands according to the code embedded in it. The coding was done using MatLab and Python tools. According to the International Organisation for Standardisation (ISO), electrically powered wheelchairs intended to carry one person must have a maximum nominal speed not exceeding 15 km/h (4.2 m/s).

4.4 Proximity sensors

Ultrasonic proximity sensors are wired into the wheelchair drive system circuitry in order to assist the user in avoiding obstacles as well as in navigation. These sensors are crucial in assisting the user in preventing crashing into obstacles when they lose control of the wheelchair. The sensors convert electric signals into ultrasonic waves which are emitted towards the four sides of the wheelchair and are reflected back to the sensor upon encountering an obstacle. Measuring the time between sending and receiving the signal allows calculation of the distance between the wheelchair and the object and using a mathematical function model encoded in the microcontroller, they estimate the brake power required to stop the wheelchair. The brake power function is consists of an exponential decrease in the speed of the wheelchair as it is brought to a halt. This allows the wheelchair to make a smooth stop without agitating the user. For the sensors on the sides of the wheelchair, the microcontroller is coded to keep a safe constant distance from an obstacle thus helping the user from steering sideways into obstacles. These abilities make the wheelchair to be conscious of its surroundings when driving. The flow chart below summarises the algorithm followed on the decision making by the system (**Figure** 7).

4.5 Autonomous elevation control

The design incorporates intelligence in its elevating mechanism to detect when the user wants to stand. Strain gauge sensors are embedded on the lower back area of the wheelchair seat and when the user is seated, these sensors are in contact with the back area. They convert force, pressure, tension, weight, etc., into a change in electrical resistance which can then be measured. When external forces are applied to a stationary object, stress and strain are the result. The strain is defined as the displacement and deformation that occur. When the user needs to elevate to standing posture, they only need to bend their upper body, leaning forwards. This results in the displacement applied on the sensors (when greater than an average) and an electrical signal sent to the Arduino microcontroller which activates:

- The braking system of the wheelchair simply by covering the front ultrasonic sensor hence triggering the object avoidance system which cuts off power to the electric motors hence braking the wheelchair. Preventing the wheelchair from moving will aid to the stability of the user and reduce chances of falling over.

- The linear hydraulic actuators and hence the wheelchair lifts the user to a standing posture.

This is illustrated in the 5 steps shown in **Figure 8** below.

When the wheelchair reaches the maximum height, a signal is sent to the actuators to stop and remain bearing the weight of the user in standing posture. When the user needs to change from standing to seated posture, they can easily press the sit button on the joystick module. This reverses the direction of actuation of the lifting mechanism hence lowering the wheelchair back to its nominal position (**Figure 9**).

Figure 10 shows the algorithm followed in elevating the user to standing posture.

4.6 Autonomous reclining control

The design incorporates an autonomous intelligent reclining mechanism that is assisted by strain gauge sensors that are embedded on the top area of the wheelchair

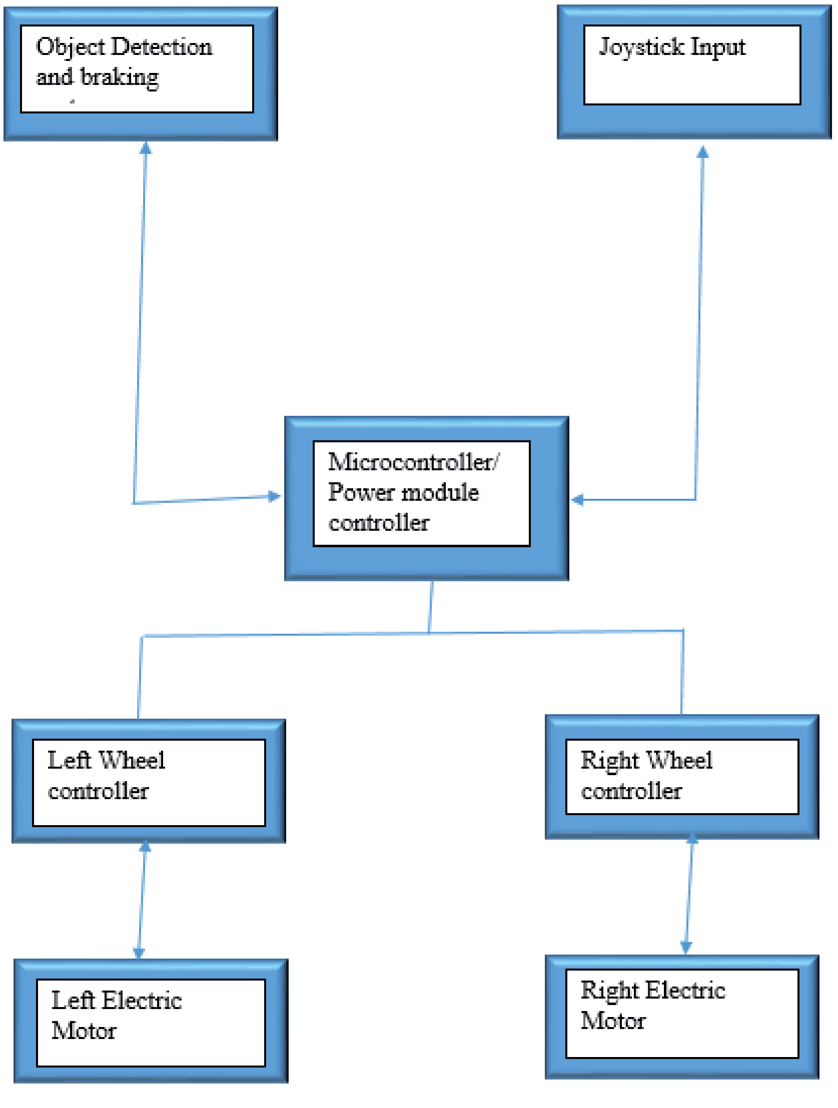

Figure 7.
Decision making algorithm flow.

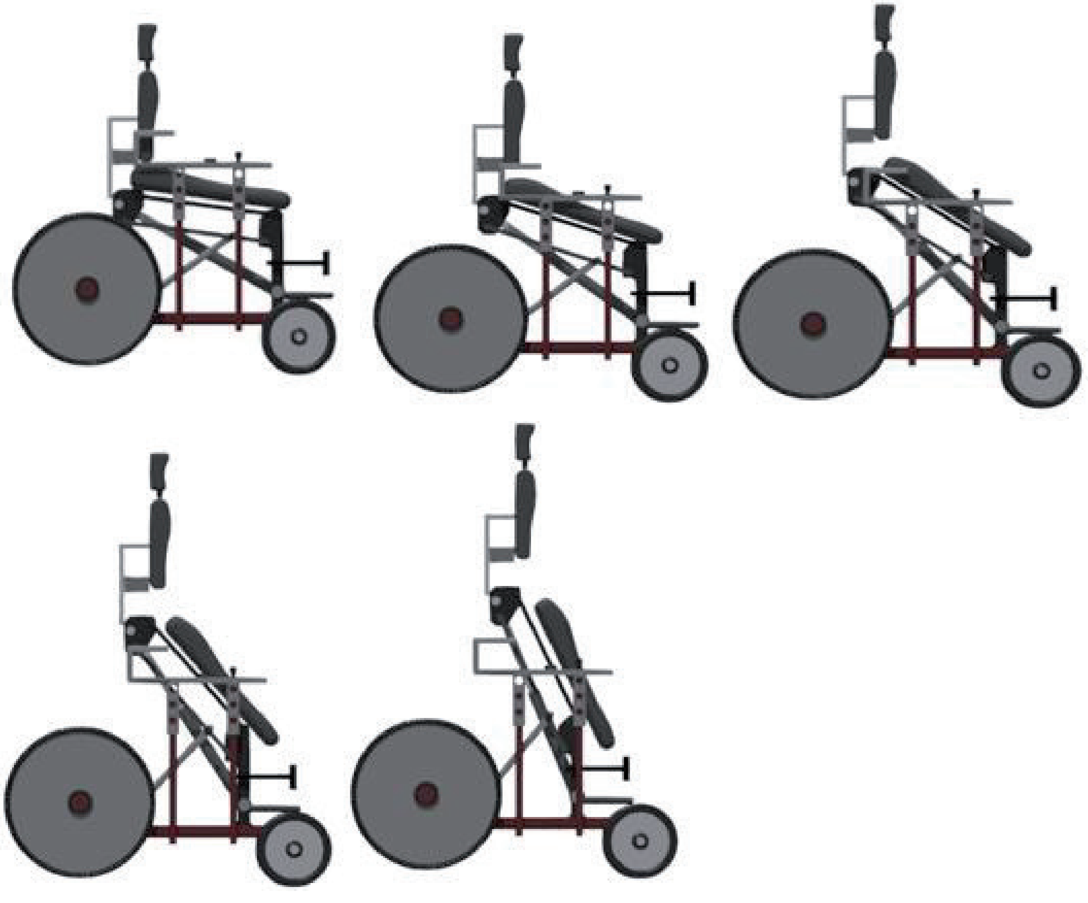

Figure 8.
Screenshots of simulation steps taken in lifting the user.

Figure 9.
Linear actuator lift and recliner concept in seated and standing posture.

head rest. When the user needs to recline the seat, they lay their head on the head rest and apply a minimum force (greater than 45 N the force applied by the weight of an average head) on the headrest (assuming the user condition allows them to do move their head). When the minimum head force is received by the stress sensors and converted to electric impulses which are sent to the control unit. This will unlock the wheelchair back rest and allow it to move backwards slowly (as

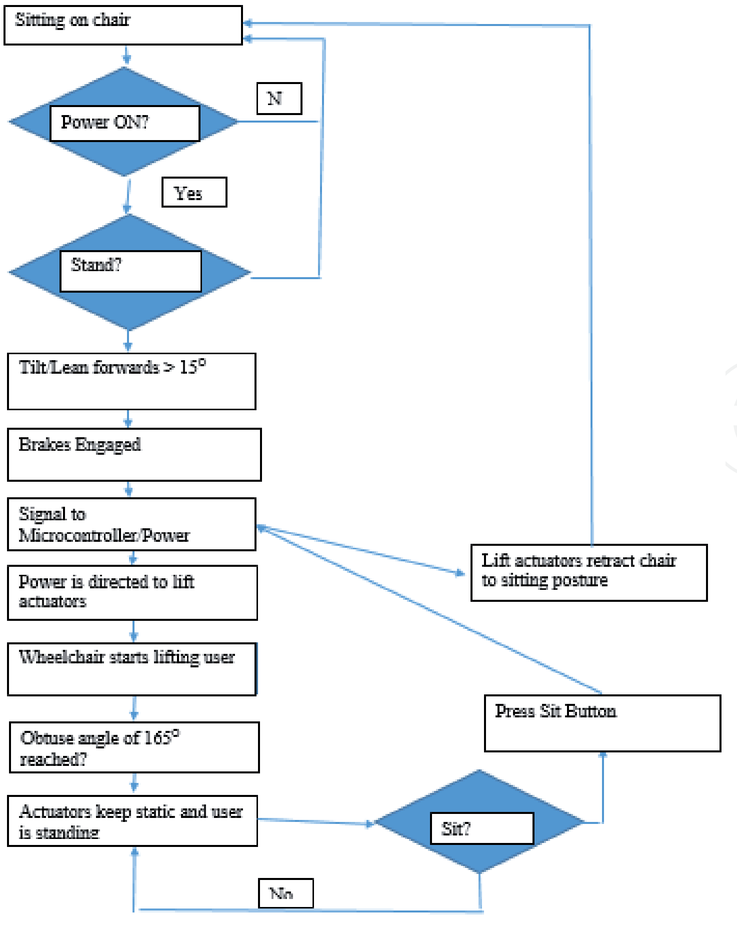

Figure 10.
Algorithm followed to elevated posture.

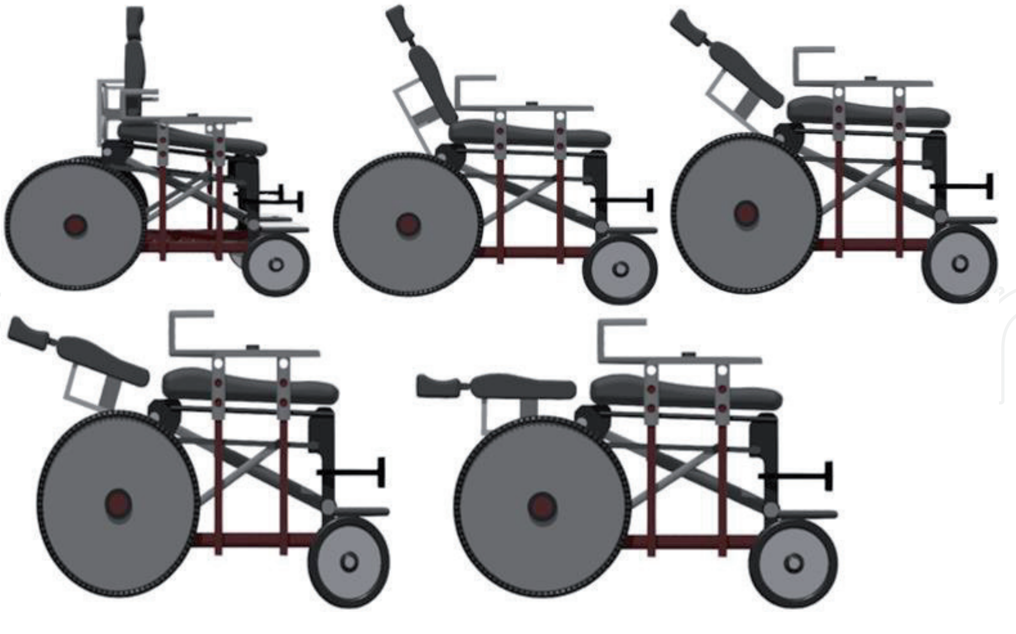

Figure 11.
Possible reclining angles.

permitted by the actuators) until it reaches an angle of tilt desired by the user. When this angle is reached, the user stops applying the force on the headrest and this sends signals to the control unit, commanding the actuators to stop reclining the seat and lock the mechanism (as the actuators will bear the load applied). The range of the reclining angles of tilt is shown in **Figure 11** shown below.

4.7 Height adjustable arm rests

The armrests are designed to be automatically adjustable up or down using a button input placed on the left arm rest of the wheelchair. The arm rests are actuated by telescoping arms that are placed in the tube of the wheelchair frame such that when they are activated, they protrude upwards, lifting the armrests to a desired height. Spiral lift telescoping arms are used for their ability to withstand the high the load exerted while projected at any height. These consist of threaded vertical profiles that move up or down inside a threaded cylinder bands that form a column. The bands are combined, separated and stored by an assembly with an electrical motor located at the base of the column and this is connected to the control unit while receiving input from the button pad on the arm rest. The desired height is determined by the duration on pressing the up/down button and on releasing the button, the armrest remain at their current height. They move simultaneously at a low constant speed that is safe for the user. When the user is in standing posture, the armrests automatically rise up for the sake of support and stability purposes.

4.8 Stability and suspension systems

The stability of the wheelchair is established by the use of four wheels instead of three and the user is supported in such a way that their centre of mass is lowered. This is also ensured by the dimensions of the wheelchair base as well as the weight and stress distribution exerted on the wheelchair. The wheelchair seat is also equipped with seatbelts/straps that help restrain the user from falling over during driving of when standing up by supporting the upper body weight of the user. The

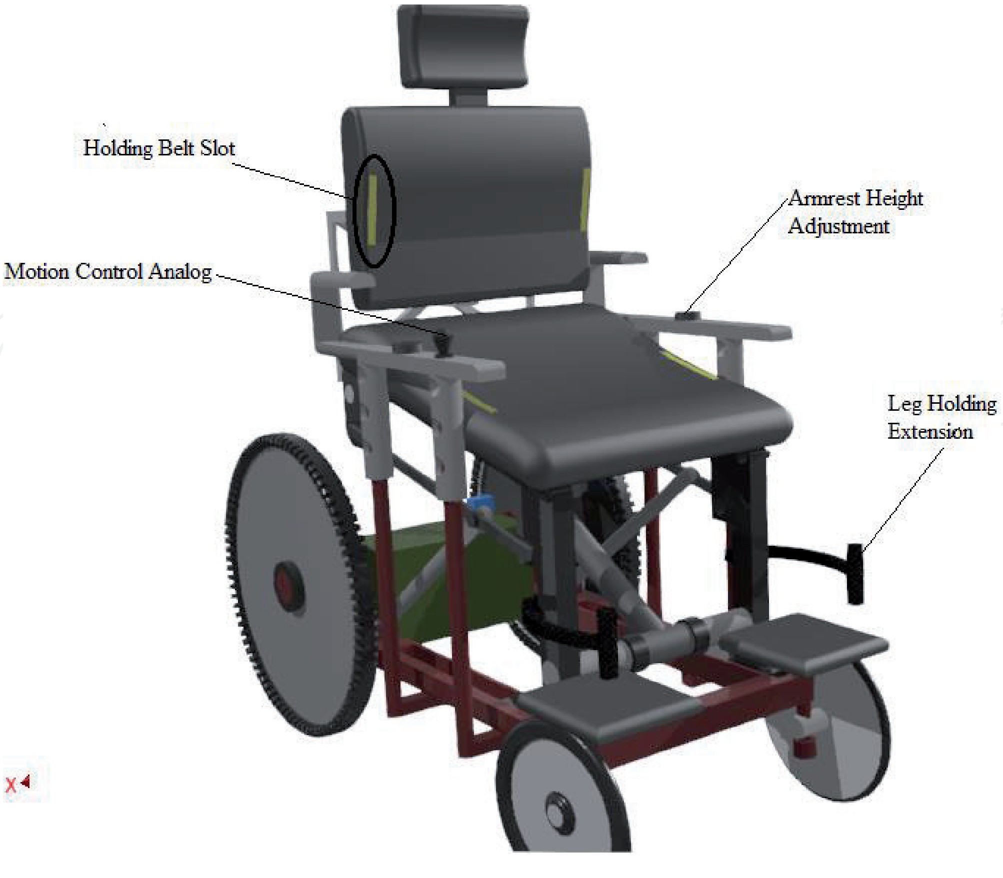

Figure 12.
Support mechanisms including seatbelt, arm rest and leg holding extension.

figure below shows the seatbelt slots on the wheelchair seat. A pair of leg holding extensions (shown in **Figure 12**) is mounted on the wheelchair in order to support the legs of the user hence aiding to the stability of the wheelchair.

The wheelchair hydraulic actuators absorb the vibrations during motion of the wheelchair along with the assistance of the wheels.

4.9 Component and materials selection

The wheelchair frame is made up of Aluminium because of its strength, light weight, corrosion resistance and resistance to shock loads that will be imposed on it during operation. Also the arm rests are also made of Aluminium as well as the spiral lift telescoping arm assembly. The leg rests are made of iron which is chosen for its high tensile strength as it will bear the body weight of the user when standing up. The seat, back and head rest are made up of silicone and are covered in foam cushion to enhance comfort to the user. While the wheels are made of rubber because of its excellent ability to absorb shock.

The joystick module which controls the power of wheelchair consists of command buttons and a knob. The module has 8 button commands namely:

- Power button-This switches the wheelchair system ON/OFF.
- Left- Steers left.
- Right – Steers right.
- Go- Moves the wheelchair forward.
- Back- Reverses the wheelchair.
- Stop- Brakes the wheelchair.
- Sit- Lowers the seat elevation system when the user needs to sit.
- Recline- Raises the seat recline back towards the initial seat angle of 90 degrees.

The joystick module is connected to the wheelchair's microcontroller/power module and these two communicate with each other using serial communication protocols. The speed and steering commands that are input by the user are converted to data packets by the internal processor of the joystick and then sent to the microcontroller via serial communication.

Finally the microcontroller module is the main system of whole wheelchair and it receives all commands from the joystick module and translates the commands into high current signals to the motors and mechanism actuators, receiving power from the 24 V battery power. Despite its small size, the power module is able to deliver a very high current per electrical motor and actuator.

4.10 Economic analysis

An effort was made to compile the cost and quantities of raw materials, and components as well as the cost of manufacturing a prototype. The grand total cost was about USD 1 511.

Part Name	Description	Cost per unit ($)	Quantity #	Total Cost ($)
Assembly Chassis	Hollow square steel tubes per meter	6.00	8	48.00
Wheelchair Frame	Aluminium Steel	9.00	6	54.00
Leg rest	Stainless Steel	6.50	2	13.00
Motion Links	Aluminium Steel	9.00	3	27.00
Leg Retainer	Aluminium Steel	9.00	2	18.00
Wheel Axle	Chrome molybdenum steel	8.00	2	16.00
Wheel bearings	Chrome Steel-SAE 52100	7.50	2	15.00
Wheel Shaft	SAE grade 41xx steel per meter	6.00	1	6.00
Arm rest props	Chrome Steel tubes per meter	8.50	4	34.00
	Total Material Cost			231.00
Electric motor	Speed differential electric motors coupled to wheel- 200 rpm, 2kw	79.00	2	158.00
Rear Wheel	Rear Rubber Wheel- 600 mm diameter	48.00	2	96.00
Front Wheel	Front Rubber Wheel-300 mm diameter	32.00	2	64.00
Head Rest, Seat Cushion, Back Rest	Foam rubber and leather covering per square meter	8.00	3	24.00
Linear Actuator	Hydraulic Linear Actuator	22.00	3	66.00
Ultrasonic Sensors	Ultrasonic Distance Sensor Module-HC-SR04	7.00	4	28.00
Strain gauge sensor	Load Cell transmitter with high accuracy	24.00	12	288.00
Joystick	Electric wheelchair joystick controller 24 V Anderson connector	80.00	1	80.00
Microcontroller	Arduino microcontroller A000079 Motor Shield, R3, 5 V–12 V	50.00	1	50.00
Battery	12 V Lead-Acid battery	60.00	2	120.00
Telescoping arm	Low noise waterproof 1500 mm Stroke 12 V/24 V telescoping linear actuator	19.00	2	38.00
Seat belt	Polyester and Nylon Seat belt straps- 900 mm	11.00	1	11.00
Connecting wires	Solid wire kit-6 different coloured spool per meter	3.00	4	12
	Total Component Cost			1 035.00
Manufacturing Process		Total $		
Welding		70.00		
Machining and Milling		80.00		
Riveting		20.00		
Miscellaneous		75.00		
TOTAL MNFNG COST OVERALL COST		245.00 USD 1 511		

Table 4.
Bill of quantities (BOQ).

From the costing analysis and evaluation carried out above, the wheelchair design proved to be relatively affordable compared to other wheelchairs on the market that can operate similarly.

4.11 Design validation summary

The evaluation of the design against the customer requirements as summarised by the **Table 4** below.

The design is fully automated with the drive, lift and recline mechanisms being controlled autonomously. It assists the user in elevating and reclining easily with use of sensors and intelligent awareness that prevents accidents and collisions. The design mechanism takes about 10 seconds in elevating to max height which makes it safe and efficient in handling the user with delicacy. The wheelchair allows the user to move around easily as well as perform more activities independently with the assistance of the wheelchair intelligence system. The design also includes a charging port to charge the battery (**Table 5**).

5. Recommendations

One key area of improvement is on the aspect of enhanced wheelchair comfort. Most wheelchairs should suit personalised seat dimensions and leg rest sizes. This could easily be incorporated into the wheelchair design.

A deeper ergonomic analysis should be conducted to improve the shapes of parts the user interacts with such as the armrests and the seating so that they provide enough comfort for long hours.

Leg supports can be added to assist in holding the user in standing posture so that they do not fall over. Also comfortable cushion material could be used for the seat and armrests such as foam padding. This can also be added to the leg supports so that the user is comfortable when standing up. The seat height at lowest elevation could be reduced to accommodate smaller body sized users.

Some considerations could be considered to change tubular material to reduce the weight of the chair. Titanium could be a good alternative to aluminium due

Criteria	Customer Requirement
Safety	Stable
	No harm to user
Mechanism Functionality	Autonomous
	Durable
	Minimum effort in operating wheelchair
	Same personal mobility as standard wheelchair
Wheelchair Functionality	Easy to move around
Geometry	Comfortable
	Cater for average user height
	Dimensioning to allow for manoeuvring.
Cost	Affordable

Table 5.
Validation of customer requirements with the design.

to its very high material strength with relatively lower weight. This change would increase the cost of the chair however and must be considered in the design.

To assist users who cannot use the remote control, future work can be done to use voice input commands to operate the wheelchair. Also some work can be done to link the wheelchair to the internet so that it can show locations, routes and report functionality levels of all parts thereby making it easy for maintenance of the wheelchair to be undertaken.

6. Conclusion

A study was done on the wheelchairs currently on the market as the basis to assess the extent to which existing mechanisms address the needs of the users. Some effort was made to gather relevant information from physically challenged wheelchair users, physiotherapists, doctors and wheelchair equipment supplying companies to establish areas of possible improvement with regards to ergonomic aspects of the wheelchair. Hydraulic linear actuator lift and recliner design concept was found to be the optimal design solution, and it was developed to come up with wheelchair characteristics, specifications, control systems and choice of construction materials. Engineering analysis and simulation were carried out to confirm the feasibility of the design. Also recommendations for future work were made on the areas that were not perfected by the design of this project, such as the need for voice input commands in the control of the wheelchair.

Acknowledgements

We would like to thank the Baines Avenue Clinic staff for allowing the researchers to interact with wheel chairs users and for the insight into health requirement for users. The Baines Physio Clinic gave us a detailed preview of how the wheel chair could contribute to the patient's physical wellbeing. Also the team from Wheelchairs Zimbabwe Company allowed us to appreciate the current wheel chair trends on the market and customer preferences.

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