Design Improvement of Off-road Rough Uneven Rural Terrain Wheelchair

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Abstract

This design study reviewed the redesign of a manual wheelchair for the rural terrain where difficulties are faced in maneuvering the currently existing wheelchairs due to uneven and rough terrain particularly with sandy, sloping ground, and poor road system which makes moving almost impossible. Possible concepts which address these challenges were developed, evaluated and improved to come up with a mechanism that takes into account the lack of balance and difficulty in maneuvering. A detailed design was done including the calculations, generation of drawings of the component parts and sizing of the parts of the wheelchair. The wheelchair was designed for occupants of healthy upper torso with pelvic to foot restraint.

1. Introduction

A wheelchair is an assistive device which enhances personal mobility and facilitates participation, for a person with walking limitation. It is estimated that over 75% of the world's population lives in rural areas, where standard conventional wheelchairs just do not work: as they are hard to push, they break easily, and cannot be repaired easily. Wheelchair designs vary to enable users to safely and effectively use their wheelchairs in the environment in which they live and work(Cooper, 2008). A wheelchair that is used primarily in rough outdoor environments needs to be robust, more stable and easier to propel over rough and uneven ground. Disabled people in rural areas are facing problems with the current available conventional 4-wheeledwheelchairs because of uneven and rough terrain especially with sandy, stony, sloping ground, steep ramps and poor road systems which make moving these manual wheelchairs almost impossible. These wheelchairs do not fully meet the needs of the users such as to travel longer distances, therefore, there is a need to come up with a wheelchair design that can be used in the rural environment and terrain without any constraints.

2. Literature Review

2.1 Wheel concept and functions

A wheelchair is a device that comes in variations allowing either manual propulsion by the seated occupant turning the rear wheels by hand or electric propulsion by motors. There are often handles behind the seat to allow for different individuals to push. According to the world health organization, a wheelchair is an assistive technological device which enhances personal mobility, promotes functional independence and facilitates participation, for a person with walking limitation. (Cooper RA, 2002).Wheelchair design and functionality as a whole has been greatly improved over the past several years, but there is still a need for new technology and innovative designs. A basic manual wheelchair incorporates a seat, foot rests and four wheels: two caster wheels at the front and two large wheels at the back. The two larger wheels in the back usually have hand rims; two metal or plastic circles approximately 3/4" thick. The hand rims have a diameter normally only slightly smaller than the wheels they are

attached to. Most wheelchairs have two push handles at the top of the back to allow for manual propulsion by a second person. The manual wheelchairs are further categorized into rigid frame type and folding frame type. The user propels the wheelchair by pushing on the hand rims, which are normally made of circular tubing attached to the outside of the large wheels. The hand rims have a diameter that is slightly less than that of the rear wheels. Other manual wheelchairs use chains and sprockets. The chain is attached to hand pedals, allowing the user much more efficient propulsion than would be provided from the push rims on a manual wheelchair. The wheelchair is propelled by the hand pedals. The hand pedals are connected to the front wheel hub with a chain wheel by a bicycle chain via gear sprockets. While on the other end, electric wheel chairs are less portable and weigh considerably more than manual wheelchairs. They require additional maintenance and are very expensive. There is decreased maneuverability, especially on certain terrains that are too rough. A wheel chair is appropriate when it meets the user's needs and environmental conditions, provides proper fit and postural support, is safe and durable.

2.2 Off road terrain

In rural areas paved roads and sidewalks are non-existent, and locations are linked only by a network of rough and uneven paths (Chakwiriza J, 2010). In such conditions, a conventional wheelchair provides limited mobility and for people with disabilities, their ability to support themselves is restricted. In the rural areas conventional push rimpropelled wheelchair are inefficient to propel and are exhausting to use for long distances on rough roads; therefore hand-powered tricycles, which are often preferred by users have adequate torso stability and are more efficient to propel than a wheelchair but are difficult to maneuver on soft ground and up steep hills. Off road wheelchairs have to be more stable and easier to maneuver on rough ground. These off road wheelchairs are made in order to prevent its rolling which is the rotation of the wheelchair around the horizontal axis and do not allow dynamic changes in the camber angle or tilting. A suspension system is normally used on the off road wheelchairs that allows the chair to keep all wheels in contact with the ground for stability while moving over rough terrain.

2.3 Center of gravity

A wheelchair needs to have a greater balance especially when moved in order to avoid toppling of the wheelchair due to unbalances. The location of the center of gravity has to be taken into account. The center of gravity (CG) of an object is the point where it can be balanced. The center of gravity is useful on the seat, frame, wheels and foot rests. The wheelchair must have a back pad to improve tipping stability. The force that is exerted on the wheelchair due to the weight of the person must be equal to the forces exerted by the ground on the rear wheelchair wheels and the front wheels so as to balance the wheelchair.



Figure 1. Forces acting on the wheelchair and variability on the centre of gravity on steep ramps (Amos winter 1999)

The wheelchair has to be designed putting into consideration the variability of the center of gravity when the wheelchair is moved on steep ramps. Some form of balancing such as the use of side small balancing wheels can be used to avoid tipping of the wheelchair on steep ramps. The wheelchair must have a fixed frame with a folding backrest and detachable rear wheels. This makes the chair more stable and easier to operate. The fixed frame also means that the framework lasts longer before maintenance is needed. The understanding of the center of gravity location is important in the wheelchair design.

2.4 Wheel chairs with sensors

Some power-assisted wheelchairs have force or moment sensing push rims that provides additional torque to the rear axle proportional to the applied force. The torque sensors amplify the force applied to the hand rim to provide a greater turning effect (Petersson 2007). In the voice activated power wheelchairs, when user speaks commands, a microphone in a throat detects the vibration of vocal cord and sends the signal to the control system which then interpret the signal and take the correct action. It is unstable for powered wheelchair control in noisy environments.

2.5 Rural challenges for wheel chair usage

The physical environment in the rural areas presents a challenge the roads are not sealed and are deeply corrugated causing great difficulties for those using wheelchairs; as they are hard to push and break easily. In the wet season the roads are mostly often flooded and boggy, making moving with the wheelchair around the community difficult. The climate of extreme heat, humidity and cold, dust and wet weather is hard wearing on the material and construction of the wheelchairs. The current conventional off road wheelchairs still have their shortcomings or limitations in maneuvering in the rural terrain that makes it difficult for the users to reach full independence. Going uphill is almost impossible due to both the difficulty of propelling and the risk of the wheelchair toppling over, causing the user to fall down on the ground leaving the user to have assistance from another person. Therefore, there is a need for a next-generation off-road wheelchair design that suits the uneven and rough terrain of the rural areas.

3. Design concept generation

The concept generation seeks to come up with a design solution to address the shortcomings of the existing wheelchairs. Thus the ability to deal with the difficulty in maneuvering in the uneven and rough rural terrain; which is physically sandy, stony, and sloppy, and at times has steep ramps; which in the process renders insufficient balance when traversing along steep ramps and banked surfaces.

Concept 1 - Anti-tipping and balance wheels: A push-rim with a diameter less than that of the rear wheel is attached on the sides of each of the rear wheels. These push-rims are used by the user to propel the wheelchair by a forward push applied on the push-rims. Two balance wheels are mounted on the sides and one anti-tipping on the back of the wheelchair to balance the wheelchair on uneven or sloppy ground. The anti-tipping is designed to minimize the risk of the wheelchair tipping fully backwards when a user loses balance.





Figure 2. Concept 1 Anti-tipping balance wheels

While this looks a robust concept, it has decreased maneuverability, especially on terrains that are extremely rough. Also it was noted that its operation is not suitable for longer distances, and the castors can easily get stuck in a terrain with many humps.

Concept 2 – **Manual weight balanced wheelchair:** Reasonable weights are added underneath the wheelchair frame to lower the center of gravity and to increase the balance of the wheelchair when traversing along the rough and uneven terrain. A push-rim which has a diameter less than that of the rear wheel is attached on the sides of each of the rear wheels. These push-rims are used by the user to propel the wheelchair by a forward push applied on the push-rims.



Figure 3. Weight balanced wheelchair

This mechanism provides increases balance during operation, while the increased weight calls for more energy to provide propulsion effort, and again the caster wheel easily gets stuck in the humps.

Concept 3 – **Three-wheel balanced wheelchair:** The mechanism uses three wheels which are always kinematically constrained to the ground and provide greater balance of the wheelchair. In this mechanism, a sprocket with hand pedals is fixed at one end of a lever bar near the user. A chain connects this sprocket to another sprocket at the other end of the lever bar . The wheelchair is propelled using the hand pedals by a cyclic forward movement of the hand pedals. The wheelchair uses a coaster brake mounted together with the hub at the front wheel and the brake is applied by a cyclic backward movement of the hand pedals.



Figure 4. Concept 3 three wheel balanced wheelchair

The concept is easy to propel and can be used off road with greater stability. On the downside, the design cannot be used in confined space. Binary dominance matrix analysis method was applied to the three concept mechanisms based on a combination of the comparative advantages and disadvantages of each. Concept 3, for three wheel balanced wheelchair was selected for further development as it greater stability, ease of operation and fully suits the rough and uneven terrain.

4. Detailed design

Much effort was put on improved stability of the wheelchair, design of the gear sprockets, design of the chain drive, braking system and gear shifting. The wheelchair consist of three wheels, two rear wheels of 650mm diameter and one front wheel of 400mm diameter. Three wheels have the advantage that they are always in contact with the ground and they provide greater balance for the wheelchair.



Figure 5. Detailed design concept

The wheelchair is propelled by hand pedals using a cyclic forward movement of the pedals. The wheelchair uses a coaster brake mounted together with the hub at the front wheel and the brake is applied by a cyclic backward movement of the hand pedals. The wheelchair is steered by moving the hand-pedals sideways. The wheelchair is 1.80m in overall length and is 0.80m wide. The overall height of the wheelchair from the ground is 0.99m.

4.1 Sprockets and chains

The gear sprockets are assembled at the front part of the wheelchair. They are connected by chains which rotates the sprockets when the user rotates the hand pedals. The first chain connects the sprocket with hand pedals fixed at one end of a lever bar near the user to another sprocket at the end of the bar. A second chain connects another sprocket at the end of the lever bar to a sprocket at the hub mounted at the front wheel.

4.2 Chassis, tubular frame and anti-tipper wheels

The chassis supports the body-support system which entails the seat and armrest. The rear wheels are mounted on the axles which are fixed at the sides of the chassis. From the chassis are connector rods which hold the plate where footplates are positioned. The chassis is made of rectangular bars of 0.05m by 0.03m. A tubular frame was developed and assembled on the wheelchair. This frame connects the plate frame which has the footplate to the front part which has the sprockets, chain and the front wheel which is mounted at the fork ends of the front part. The tubular frame is 80mm in diameter and 2mm thickness. Anti-tipper wheels are mounted at the back of the chassis. The anti-tipper wheels can be dismounted when not required to be used. These prevent the wheelchair form toppling backwards when ascending steep slopes. The anti-tipper wheels can be also mounted on the axle of rear wheels to increase balance when traversing along banked surfaces.

4.2 Seat, Backrest and arm rest

The seat is where the user seats when using the wheelchair. It is made from a cushioned sailcloth foam. The cushioned foam for the seat can be replaced if it is no longer comfortable. The backrest of the wheelchair is upholstered and is covered with a cushion. The cushion is easily replaced for a new one. The armrests are fixed and are well cushioned for comfortable resting of hands. The clearance between the seat and the armrest is 0.14m

4.3 Footplate, hand pedals, wheels and axles

The footplate is made of a flat plate metal sheet that stabilizes the chair's frame and also provide a comfortable surface to place the feet on. The footplate is adjustable by use of an adjuster arm. The footplate provides better body position and protection of feet. The hand pedals are used to propel the wheelchair by a forward cyclic motion of the hand pedals. The hand pedals are 0.14m in length. They have a plastic rubber to provide a greater grip of the hands. The rear wheels are mounted on the axles fixed at the chassis of the wheelchair. The rear wheels are quick-release which enables them to be assembled or disassembled easily. The front wheel is mounted at the fork ends. The wheels are the same as those used on bycicles. There are two axles mounted on the lower left and right side of the chassis. The rear wheels are mounted at these axles. A third axle is mounted at the fork end where the front wheel is mounted. The axles are 0.076m long and 0.017m in diameter.

4.4 Choice of design of gear sprockets

Gear sprockets were chosen as they transmit exact velocity ratio, and deliver high efficiency as well as allow for a compact layout. All the three sprockets were sized according to Indian Standards (IS: 2403 — 1991).

Sprocket 1:	Pitch circle diameter : Diametral pitch: Circular pitch: Outside diameter: Module:	$\begin{array}{l} D = 160 mm \\ P_d = 0.25 mm \\ P_c = 12.57 mm \\ 166 mm \\ m = 4 \end{array}$
Sprocket 2:	Pitch circle diameter : Diametral pitch: Circular pitch: Outside diameter: Module:	$D = 72mm P_d = 0.25mm P_c = 12.57mm 78mm m = 4$
Sprocket 3:	Pitch circle diameter : Diametral pitch: Circular pitch: Outside diameter: Module:	D = 80mm $P_d = 0.25mm$ $P_c = 12.57mm$ 86mm m = 4

Sprockets thickness= 0.93 * roller width - 0.15 = 0.93*6.25 -0.15 = 5.6625mm

4.5 Chain design selection



Figure 6.Chain configuration

Chain drive was chosen to give perfect velocity ratio with no slip, giving a high transmission efficiency, as well as permiting high speed ratio.

For sprocket 1 and 2:	Velocity ratio: Centre distance:	V.R x	= =	2.2 548mm
	Number of chain links:	Κ	=	116
	Length of chain: $L = K^{2}$	* p = 11	6*12.5	=1450mm
For sprocket 2 and 3:	Velocity ratio:	V.R	=	1.1
	Centre distance:	Х	=	700mm
	Number of chain links:	Κ	=	130
	Length of chain: $L = K * p = 130*12.5 = 1625 mm$			

4.6 Design of shaft axle

The diameter of the shaft is related to the maximum torque, T_{max} and the allowable shear stress, of the material, τ by the equation $T = \frac{\pi}{16} \tau d^3$. For the shaft the material was mild steel because of its high strength. The ultimate tensile strength of this material is 615.4 MPa. The value of shear stress will be taken as 0.8 * UTS.

Therefore $\tau = 0.8*615.4 \text{ MPa} = 492.4 \text{MPa}$

The maximum value of torque will be estimated from the mean torque at the maximum speed of the wheel. It shall be assumed that the maximum torque is 20 times greater than the torque. Shaft diameter, d = 20mm

4.7 Design for stability and tipping angle

The force applied on the wheelchair due to the weight of the person must be equal to the force applied on the wheels by the ground for the wheelchair to be stable. The average weight of people is between the range of 62kg to about 70kg (www.biomedcentral.com). The average weight used in the calculation for stability was 65kg.

Average weight, W = 65 * 19 N = 650 N



Figure 7. Free body diagram

Equations obtained from the manual : Mechanical Principle of Wheelchair design (Winter 1999)

 $2F_{RW} + F_{FW} - F_{PERSON} = 0 \qquad \text{where } F_{RW} = \text{force exerted by the ground on the rear wheels}$ $2F_{RW} + F_{FW} - 650 = 0 \qquad F_{FW} = \text{force exerted by the ground on the front wheel}$ $F_{PERSON} = \text{force exerted on the wheelchair by the person}$

Taking moments about F_{FW}

 $650(0.75+0.2+0.08)-2F_{RW}(0.75+0.20+0.325)=0$

$F_{RW} = 239.11N$

Substituting the value of F_{RW} in equation above $F_{FW} = 171.78N$

And now the **maximum angle of tip** occurs when the line of action of the force due to the weight of the person is collinear with the line of centre of gravity.



Figure 8.Angle of tip

Equations obtained from the manual : Mechanical Principle of Wheelchair design (Winter 2007)

Taking h_{tip} as 0.4m Width of the wheelchair, A=0.70m

$$\alpha_{\rm tip} = \sin^{-1}(\frac{\rm htip}{2A}) = \sin^{-1}(\frac{0.40}{2(0.70)}) = 16.6^{\circ}$$

Tipping angle and height for different wheelchair geometries

Table	1	Tinn	ino	anole	for	different	wheel	chair	geometries
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$^{A}/_{B}$	α_{tip}	h _{tip}
0.3	17°	0.11m
0.4	21°	0.18m
0.5	27°	0.28m

4.8 Internal moments and forces in the rear axle

The critically loaded component of the mechanism is the rear axle (Winter 2007), using the basic bending moment equations.



Figure 9. bending moment on rear axle

F _{person}	=	650N
Ŕ	=	0.325m
L	=	0.076m

Forces

F _{person} -F _{axle-horizontal} =0	F _{person} -F _{axle-vertical} =0
650- F _{axle-horizontal} =0	650- F _{axle-vertical} =0
Faxle-horizontal=650N	$F_{axle-vertical}$ =650N

Moments

F_{person} (L) - F_{person}(R) +M_{axle}=0

 $M_{axle} = F_{person}(R-L)$

Maxle=650(0.325-0.076)

The bending moment is M_{axle}=161.85Nm

4.9 Braking system

To achieve a reasonable degree of safety, it is essential to have brakes to slow down and bring the wheelchair to a complete stop. The braking of the wheels must be possible with the use of one or both hands. Hence the braking mechanism that is efficient and easy to use is mounted on the wheelchair. Coaster brakes are incorporated within the hub where a chain drives a sprocket mounted on the hub. The coaster brakes are applied by propelling the pedals backwards. When the pedals are propelled backwards the hub system is locked preventing the wheels from sliding backwards thus breaking the wheelchair.

4.10 Gear shifting

The device needs to allow the user to climb hills. In order to accomplish this, the most likely addition would be a gear set. The mechanism should be efficient and easy to provide smooth gear shifting. Thus an internally-geared hub which can be in a range from three to twelve speeds, could be fixed to the frame to provide the earing needed to climb hills at the required speed. This does shift while the vehicle is stationary. The hub gears require less maintenance as the hub gears are sealed within the hub which protects them from water, grit, and impacts. They can also be manufactured to include a coaster brake. However, it requires re-lace of the wheels.

4.11 Material selection and sizing

The overriding motive was to select material that provides high strength and reliability to the wheelchair, as well as to reduce the material cost and overall weight of the design. In this regard steel and aluminum were used for wheelchair frame construction. These two metals have high strength to weight ratios and are easily worked into pipes and other shapes required for a standard wheelchair. Steel alloys which are commonly used for wheelchairs are AISI 1040, 1060, or mild steel, AISI 4130, or chromium-molybdenum alloy steel, and ANSI 4340, 8620, or chromium-nickel-molybdenum alloy steel. SAE 6061 or aircraft aluminum is used as it is lightweight and provides good structural support for a standard wheelchair. Titanium and titanium alloys are also used but they have a high cost and have limited availability.

4.12 Tire selection

The tires used for the rough and uneven terrain must be flat free, require less maintenance, provide greater grip on the ground and lighter. For this reason, puncture-proof tires were recommended as they are durable, reliable, cheap and easy to maintain. Basically these are made of rubber or plastic usually polyurethane material, while the inner tube consists of a solid material such as foam, rubber or plastic. These tires are flat free and require less maintenance. They are stiffer and tend to grip the ground well. These features enhance the performance of the wheelchair in remote outdoor conditions, where it is common to travel up and down inclined surfaces, over rough and rocky terrain.

4.13 Von Mises analysis

Von Mises stress analysis was carried out on the critical components, the connector rods and the chassis which are most likely to fail on impacts. This gave a measure used in the design so as to predict the yielding of the chassis and the connector rods. For a good design, the maximum Von Mises stress in the components should be less or equal to the design stress of the component. In the von Mises diagram, von Mises stresses are lowest in the blue regions and the red regions indicate the areas of highest von Mises stresses. The Von Mises stress analyses of the chassis were calculated using SOLIDWORKS 2016 Simulation because it calculates localized stresses and not gross stress to increase accuracy.



Figure 10. Von Misses stress for chassis

The maximum von Mises stress in the chassis occurs on the region where the seat is attached on the chassis. Assuming a factor of safety of 6.

The design stress

$$\sigma_d = rac{206.8 imes 10^6}{6}$$

24.24*MPa* < 34.47MPa

The maximum von Mises stress is less than the design stress of the chassis. The design is therefore safe. While the maximum von Mises stress in the connector rod occurs on the region where it joins the plate frame and is also in the safe region. 620.4×10^{6}

The design stress

$$\sigma_d = \frac{620.4 \times 1}{6}$$
=103.4MPa

22.62MPa <103.4Mpa

Hence in both cases, the results showed that the maximum von Mises in each of the tested components were well below the yield stresses of the respective components. Therefore under no normal operating circumstances shall these components fail.

4.14 Cost analysis

After the bill of quantities was drawn, the total cost of all the required component parts for the manufacture of the wheelchair was \$229, when compared with the cost of \$280 for existing unit on the market. From this amount, it could be concluded that the wheelchair is cost effective.



Figure 11. 3-Dimensional view

5.Recommendations

It was found also necessary to equip the wheelchair with a reflecting system on the rear and front end to improve the visibility of occupant, as well as making a provision for a seatbelt for safety of the user. To save on weight, the chassis and frame must be made using as little material as possible. The wheelchair has puncture proof tires which are less shock absorbing. A shock absorber can be used on the wheelchair to absorb shock in rough terrain. The anti-tipper devices or wheels must be installed on the wheelchair to ensure a safe ride. The gearing mechanism size must be able to fit within the hub and it must be light so that it does not add too much weight to the rest of the wheelchair. Because the gearing mechanism is part of the drive train of the wheelchair its efficiency greatly affects that of the whole wheelchair. Therefore a good bearing system must be used. Typical efficiencies for internal hubs in good condition are between 94% and 98%.

6.Conclusion

It has been established that the currently used wheelchairs have many challenges in maneuvering in the rough and uneven terrain in rural areas. The wheelchairs lack sufficient balance in maneuvering on steep slopes and banked roads. To address these challenges associated with existing wheelchairs, a design concept was developed for a well balanced mechanism wheelchair. A completed design of the chosen concept was carried out. The design has a provision for anti-tipper wheels to enhance balance of the wheelchair. The mechanical advantage was greatly improved by using a system of chains and sprocket for the propulsion mechanism of the wheelchair and the design is simple to operate.

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Biography

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