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Design and Modification of One Arm Driven Manual Hemiplegic Wheelchair

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This paper presents a design modification to the existing standard wheelchair by incorporating an improved propulsion system and also braking and tilting systems that allow its full control with only one hand. The proposed design has the propulsion system with a chain drive powered through a four bar linkage driven by the main handle. The desired direction of motion is obtained by moving the lever in opposite directions. Disk brakes mounted on each of the wheels are operated through a brake lever attached to the handle near the main propulsion lever. The design involves a detachable lever operated lead screw that can be fitted to a wide range of wheelchair models. The leadscrew operated lifting mechanism helps to raise the seat cushion and tilt the backrest that facilitates easy shifting of the patient to bed or stretcher, etc. The design of the wheelchair mechanism is based on the anthropometric data for transfer of clients to bed. The proposed design has the merits of the mechanical advantage of requiring lesser force to operate and improved speed of operation due to a velocity ratio of the chain drive.

Key words: wheelchair, hemiplegic, propulsion, bed mechanisms, one arm.

1 Introduction

Advancements in assistive technology for individuals using wheelchairs are continuously introduced in the medical field. These advancements mostly focus on technologies such as use of light weight composite materials and durable frames for the wheelchairs with gyroscopic sensors for self-balancing purpose, etc. The design and functionality aspects have been greatly improved over the past several decades and still there is a need for innovative designs.

Hemiplegic stroke patients are considered to be the weakest people who very much need a wheel chair with good efficiency and functionality aspects [1]. One of the commercially available and most popular type is the one-arm driven dual push rim manual wheelchair of U.S. Patent 5306035 [2] as shown in Figure (1).

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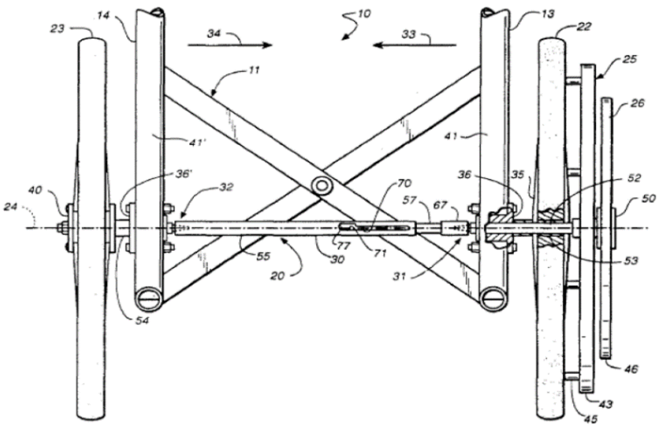

Figure 1 Dual-Rim Wheelchair (US Patent #5306035)

In this, the propulsion is given only on one side and manual manipulation and control requires both the arms that gives strain to the individual, especially for the hemiplegic stroke patients.
The U.S. Patent 5007655 [3] describes a wheel chair shown in Figure (2) that is operated by levers arranged on both sides. These levers are connected to the sprockets mounted on the drive wheels. There are two versions of this wheel chair with a variation in connection of the levers to the sprockets. This wheelchair has the disadvantage that it cannot be propelled backwards. It requires that the drive mechanism be disengaged and the wheels are to be propelled manually using push rims. The transfer of patients from the wheelchair to bed or stretcher or from bed to wheelchair is a labor intensive work while using these wheelchairs, requiring more than one person and sometimes dangerous to the patients.
Tsai, et.al. [4] have developed a prototype of unilaterally propelled wheelchair(UPW) for hemiplegic stroke patients which can be propelled by the unaffected arm and leg. A crank-rocker linkage of a planar four bar chain mechanism was used for driving the wheel chair. The clinical evaluation of the prototype this wheelchair has indicated superior performance in terms of velocity, deviation frequency and deviation period compared to the commercially available two-hand rim propelled wheelchair (TPW).
Kundu, et.al.[5] have developed an innovative 4 wheeled omni-directional wheelchair incorporating an intention based myoelectric control with hydraulic suspension system to facilitate equal load distribution on the wheels. The myoelectric control uses a classification algorithm where the intention of the user is mapped to seven different motion commands of the wheel chair. The neural network toolbox in MATLAB has been used to classify the motion. The wheel chair is operated throughjoy stick. Yin Chen, Zhong Wu, Hongyu Deng [6] have presented an optimum design for Standard Manual Wheelchair with a provision to slide the seat to back and forth to suit the timely need of the user. They have employed light weight composite materials for the construction of load bearing parts. It is purely driven by a second person hence no drive mechanisms are considered. Cassidy, et.al. [7] have developed a one-arm driven wheelchair with a linkage connected to ratchet and pawl type transmission system and a cantilever type cable operated braking system. DiGiovanni, Dominic, Marrion, Valerie, Nina, Hamlet [8] have improved the propulsion by assembling a dual gear pawl assembly in place of the ratchet and pawl assembly of Cassidy, et.al. [7]. The dual pawl is attached to the coupler link is actuated by the rocker arm which is the hand lever itself. The gear forms the crank link of the four bar mechanism.

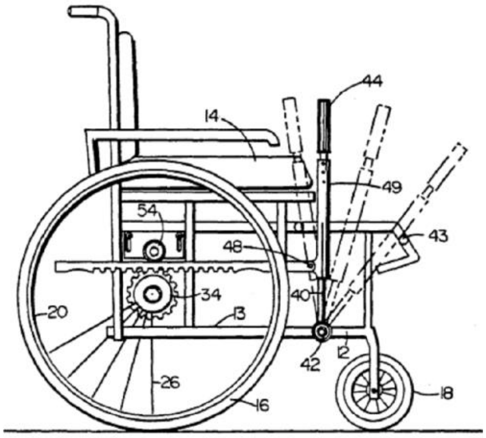

Figure 2 Sprocket- rack arrangement (U.S. Patent #5007655)

This dual pawl gear assembly can propel the chair in either direction. A cable operated disk brakes are mounted on each wheel. Jennifer and Margaret [9] have conducted study of several people with neuromuscular disabilities for the anthropometric data and suggested appropriate dimensions for seat depth, arm rest height, backrest height and contour support, etc., for a design modification of the existing wheel chairs. The proposed design has the propulsion system with a chain drive powered through a four bar linkage driven by the main handle. This design has the merits of mechanical advantage of requiring lesser force to operate and vary the velocity ratio of the chain drive. Further, other accessories are added for lifting mechanisms to raise the cushion and tilt the back rest that facilitate easy shifting of the patient to bed or stretcher.

2 Conceptual Design

Conceptual design involves the design process to identify the essential problem through abstraction and establishing function structures, searching for appropriate working principle to develop a working model [10]. Designers mostly focus on the needs that are not so far addressed in the market or to produce the existing products with improvements.

In this direction, there has been a brainstorming approach to improve the existing hemiplegic wheelchair to satisfy the user's needs in different aspects. The results of the survey on different features required for the wheel chair is summarized in Figure (3).

2.1 Quality function deployment

The House of Quality (HOQ) takes information from the design team and translates it into a format that is more useful for new product development [11]. The HOQ shows that the most important Engineering Characteristics (EC) to the modification of hemiplegic wheelchair are the selection of mechanisms, overall dimensions, ergonomics, change of material, and aesthetics. The selection of appropriate mechanism ranked first.

These ECs are very much essential for achieving the desired objective. The overall dimensions of the accessory produced shall appropriately fit in the selected type of manual wheelchair. Weight of the wheelchair has come as the low ranking EC and increase in weight by additional items attached during design modification doesn't directly affect the propulsion and other wheelchair mechanisms.

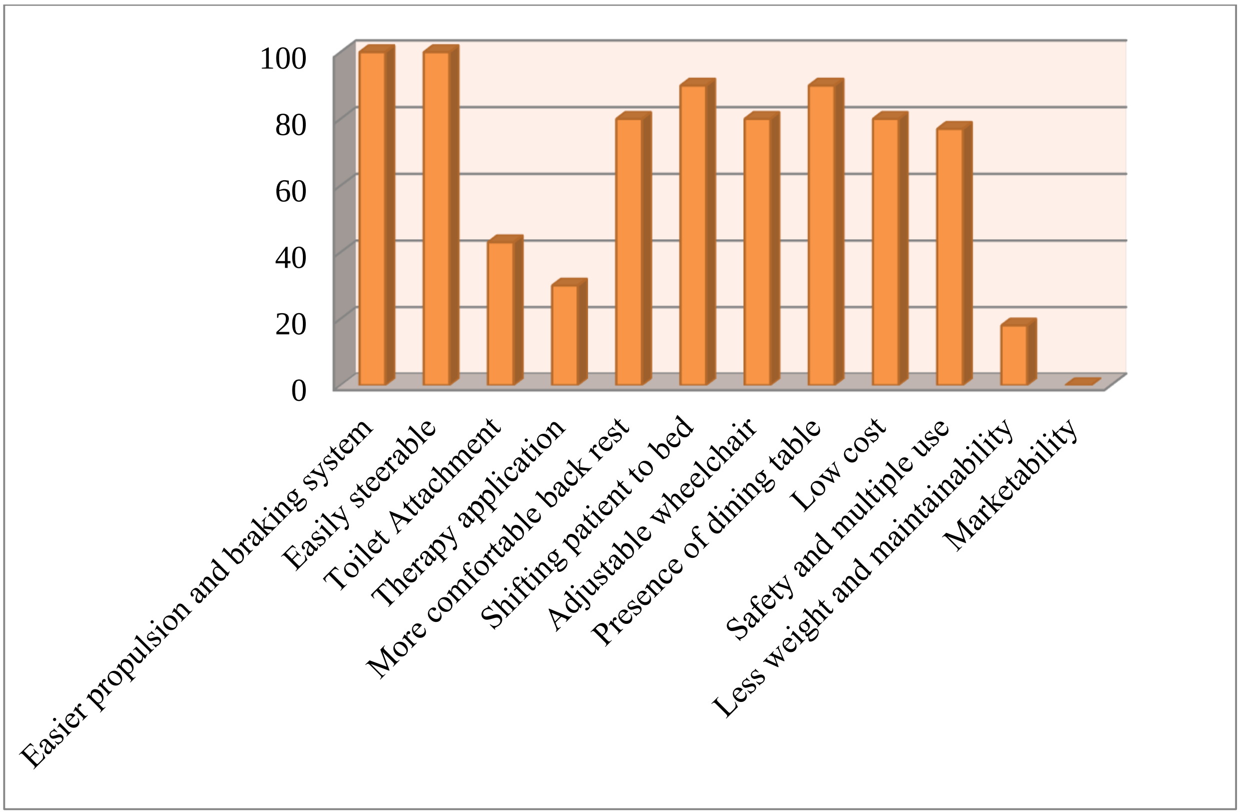

Figure 3 Frequency of response vs features of wheelchair

2.2 Working solution variants

The selected ECs that are critical to quality (CTQ) are broken down into subcategories of propulsion, braking, steering, mechanism for shifting to bed and selection of a comfortable back rest. The following points indicate the process and criteria adopted to arrive at the final design.

a. Arrangements for steering, braking, and forward/backward propulsion shall be placed only one side of the wheelchair and they are to be performed by only one arm.
b. The overall dimensions of the wheelchair should be acceptable.
c. The overall weight of the chair shall not exceed twenty kilograms even after adding the accessories.
d. Considering the disability of the hemiplegic patient, the effort required to operate shall not be too extreme.
e. The wheelchair can move at velocity maximum up to 0.5m/s.
f. Wheelchair modification accessory should be easily detachable.
g. Components should be pleasing aesthetically.

h. Components should be universal.

Table 1 House of quality

Relationship matrix: ✓ 9 Strong ✓ 3 Medium ✓ 1 Weak	Importance rating of CR: 1 irrelevant, 5 Essential							
	Engineering characteristics							
Improvement direction	↑	↓	↑	↑	↑	↑	↑	↓
Units	n/a	m	n/a	n/a	n/a	n/a	n/a	kg
Customer requirement	Importance rating	mechanism	Overall dimensions	Aesthetics	Change of material	Safety	ergonomics	Weight
1.Easier propulsion and braking system	5	9	9	9		9	9	3
2.Easily steerable	5	9	9			9	9	3
3.Therapy application	3							
4. shifting patient to bed mechanism	4	9	9			9	9	
5.Toilet attachment	2	1						
6.Adjustable	4	9	9				9	
7.More comfortable back rest	4			9	9			
8. Low cost	5		9	9	9			
9. Safety and multiple use	4	3			9			
10. Less weight	4		9		3			9
11. Presence of dining table	1							
12.Maintablity	4	3						
Row score		186	243	126	129	126	162	66
Relative weight		17.91	23.41	12.1	12.4	12.1	15.6	6.4
Rank order		2	1	5	4	6	3	7

✓ Blank none

The most appropriate type of wheelchair for the intended modification is the manual standard/everyday use wheelchair. Adapting the one-arm drive accessory to standard every-day use chair will make the user base more independent by increasing their mobility capabilities for everyday use. Construction of decision matrix is the most promising approach at the concept stage. The following matrices compare different options for each subsystem against a set of criteria the team chooses the most important design considerations. The decision matrix for each design feature is provided separately with the common decision criteria being the smallest profile, estimated cost, ease of manufacturing, functionality, ease of installation, weight and adaptability of the modification to other wheelchair models.

The rank is given from 5 to 1, Irrelevant -1 Not important -2 Natural -3 Important -4 Essential-5

Table 2 Decision matrix for propulsion

	Weight	Four bar on foot rest	Slider crank	Four bar	Gear box	Chain drive	Four bar connected to chain drive
Provide forward and back ward propulsion	20	3	3	4	3	4	5
Smallest profile	10	3	4	5	3	5	4
Estimated cost	10	3	4	5	3	5	4
Easy of manufacturing	5	3	4	4	3	4	4
Functionality	20	4	3	3	4	4	5
Ease of installation	5	3	3	4	3	4	4
Noise	10	4	4	4	3	4	5
Comparable speed	5	4	3	3	4	4	5
Match with other feature	15	5	3	5	3	5	5
Total	100	365	335	410	325	435	470

Table 3 Decision matrix for brakes

	Weight	Drum Brake	Disc Brake	Cantilever Brake	Hydraulic Brake
Force required for actuation	20	3	4	2	5
Estimated cost	10	3	3	5	1
Estimated weight	5	1	3	4	1
Ease of assembly	10	3	4	5	3
Ease of maintenance	10	4	4	2	2
Match with other feature	20	2	5	2	4
Ease of installation	10	2	4	3	2
Smallest profile	15	5	4	3	4
Total	100	300	405	295	325

2.3 Working principle of manual hemiplegic wheelchair

The anthropometric data pertaining to the lengths of the body limbs to determine the position of the foot rest height of lift of cushion of the wheelchair for transferring persons from chair to bed, etc. and also is taken from the anthropometry index database developed by Jurgens, et.al.[12] at the International Labor Office, Geneva.

The conceptual one-arm driven hemiplegic wheel chair is shown in Figure (4). The manual hemiplegic wheelchair propulsion mechanism works through a four bar chain connected with sprocket for power transmission drive. First the client oscillates the lever arm towards one's self which brings rotation to the crank link of the four bar chain which gives rotation to the larger sprocket. The chain drive is connected between the larger sprocket and the sprocket attached on the shaft of the main wheel thus moving the wheelchair to the desired position.

Table 4 Decision matrix for steering

	Weight	Linkage steering	Cable steering
Provides left and right direction during Propulsion	30	5	5
Estimated cost	10	4	3
Estimated weight	5	5	3
Ease of assembly	5	4	3
Ease of maintenance	5	4	3
Functionality	10	5	4
Match with other feature	15	5	3
Ease of installation	10	3	3
Smallest profile	10	4	3
Total	100	420	370

Table 5 Decision matrix for mechanism to transfer to bed

	Weight	Screw lift mechanism	Hydraulic lift mechanism
Force required for lifting	15	4	5
Estimated cost	10	4	2
Estimated weight	10	4	2
Ease of assembly	10	4	2
Ease of maintenance	10	4	2
Functionality	15	4	4
Match with other feature	15	5	3
Ease of installation	5	4	3
Smallest profile	10	5	3
Total	100	425	305

When the client needs to reduce the speed or stop the movement of the wheelchair, he squeezes the handle on the lever arm causing tension in the cable which is transmitted to the brake assembly on the wheel thereby clamping the brake pads on the metal disc resulting in arresting the movement of the wheelchair. After an extended period of usage, the cables tend to stretch and shall be readjusted to maintain proper tension.

The propulsion lever mounted with the pivot near one of the front casters allows the linkage steering to transfer motion easily from the propulsion lever to the caster.

When the steering plate is rotated, the lever arm would transfer displacement down a linkage then the chair will take the desired direction.

Figure 4 Conceptual design of manual hemiplegic wheelchair

Figure 5 Assembly of bed transfer mechanisms on the wheelchair

When the client needs to lift up and reach to bed, first he has to lock the wheel and rotate the handle to give rotation to the lead screw. When the lead screw rotates, the nuts on the lead screw move axially in outward or inward directions thereby lowering or lifting the cushion respectively. The lead screw is supported in the bearings that allow its free rotation. The conceptual wheel chair with the bed transfer mechanism is shown in Figure (5).

3 Embodiment Design

3.1 Propulsion Design

Kinematic analysis of the four bar linkage is done to determine the proportions of the lengths of the links necessary to obtain the desired motion. The Linkage and Sam software is used to determine the proportions of the links. The motion of the four bar linkage is analyzed for both forward and reverse propulsions [13]. The displacement of link is given by a complex quantity, $z = x + iy$, where, $x = Re\ z$ and $x = Im\ z$.

$$z = ae^{j\theta_2} + be^{j\theta_3} - ce^{j\theta_4} - de^{j\theta_1} \quad (1)$$

and

$$x = a\cos\theta_2 + b\cos\theta_3 - c\cos\theta_4 - d\cos\theta_1 \quad (2)$$

$$y = a\sin\theta_2 + b\sin\theta_3 - c\sin\theta_4 - d\sin\theta_1 \quad (3)$$

The angle between the coupler and the output link is called the transmission angle (γ).

$$\gamma = \cos^{-1}\frac{r_3^2 + r_4^2 - r_1^2 + 2r_1r_2\cos\theta_2}{2r_3r_4} \quad \text{....(2.56)[13]}$$

$$\frac{r_3^2 + r_4^2 - (r_1 + r_2)^2}{2r_3r_4} \le \cos\gamma \le \frac{r_3^2 + r_4^2 - (r_1 - r_2)^2}{2r_3r_4} \quad \text{....(2.63)[13]}$$

Here, the following notation is adopted in Figure 6. $r_1 = d, r_2 = a, r_3 = b,$ and $r_4 = c$. Brodell and Soni [14] state that the transmission angle should be larger than 30^o for a good "quality " motion and even larger if high speeds are involved (p.329,[13]). They have developed an analytical method of synthesizing the crank-rocker linkage in which the time ratio *Q*=1.
The design also satisfies the condition $\gamma_{\min} = (180^o - \gamma_{\max})$ ref. p328 [13].

Accordingly, taking $\gamma_{\min} = 40^o$, the in range is considered as 40^o – 140^o. Denoting θ_3 and γ, we have,

$$x = a\cos\theta_2 + b\cos\gamma - c\cos\theta_4 - d\cos\theta_1 \quad (4)$$

For the condition that the transmission angle (γ) to lie within the safe range, the other angles are obtained from the software from eq.(1) and eq.(2) as:

$$\theta_1 = 43^o, \theta = 128^o, \theta_3 = 85^o, \theta_4 = 90^o \text{ and } \gamma = 123^o$$

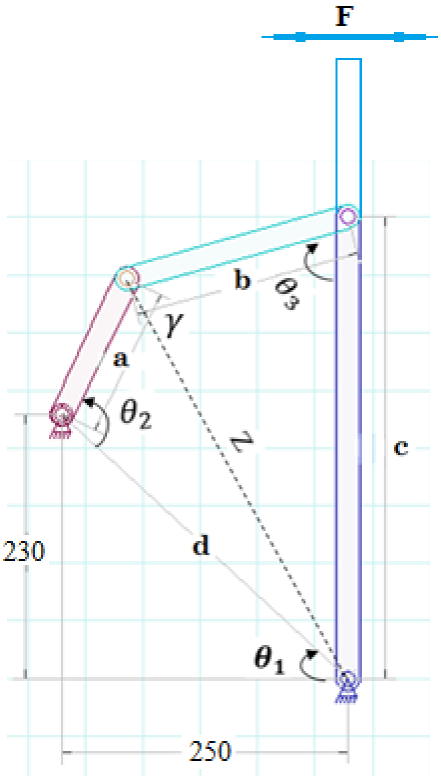

Figure 6 Four bar linkage

The velocity of various links is analyzed to satisfy the fundamental law that the sum of the position vectors of the ends of the links is zero and also the sum of their derivatives is equal to zero. To get the expression for the velocity of different links, the derivative of eq.(1) is equated to zero. The term with θ_1 is dropped as angle θ_1 is constant. We have,

$$\frac{dz}{dt}=\frac{d}{dt}(ae^{j\theta_2}+be^{j\theta_3}-ce^{j\theta_4})=jae^{j\theta_2}\omega_2+jbe^{j\theta_3}\omega_3-jce^{j\theta_4}\omega_4=0 \quad (5)$$

$$V_A+V_B-V_{AB}=0$$

Thus, we have: $V_A=jae^{j\theta_2}\omega_2$, $V_B=jbe^{j\theta_3}\omega_3$, $V_{AB}=jce^{j\theta_4}\omega_4$

$$V_A=108m/s \qquad V_B=0.19m/s \qquad V_{AB}=0.208m/s$$

The expression for acceleration is obtained by differentiating eq.(5) with respect to time, *t* and equating it to zero, we have:

$$\frac{d}{dt}(jae^{j\theta_2}\omega_2+jbe^{j\theta_3}\omega_3-jce^{j\theta_4}\omega_4)=0$$

$$(j^2a\omega_2^2e^{j\theta_2}+ja\alpha_2e^{j\theta_2})+(j^2a\omega_3^2e^{j\theta_3}+ja\alpha_3e^{j\theta_3})-(j^2a\omega_4^2e^{j\theta_4}+ja\alpha_4e^{j\theta_4})=0 \quad (6)$$

The results of the kinematic analysis of the links of the four bar chain are summarized in Table (6).

Table 6 Results of the kinematic analysis of the links of the four bar chain.

Link length*	a=130 mm	b=200 mm	c=400 mm
Angular velocity	$\omega_2 = 0.81 rad/s$	$\omega_3 = 0.95 rad/s$	$\omega_4 = 0.54 rad/s$
Angular acceleration	$\alpha_2 = -1 rad/s^2$	$\alpha_3 = 5.68 rad/s^2$	$\alpha_4 = 1.59 rad/s^2$
Linear acceleration	$a_a = 0.149 m/s^2$	$a_b = -1.146 + j0.081 m/s^2$	$a_b = -0.624 + j0.108 m/s^2$

*The fixed distance *d*= 340mm

3.2 Power Transmission

The input force for propulsion is supplied through the hand of the user on the lever which is an extension of link with length 'c' of the four bar linkage which in turn actuates the coupler link, 'b'w that in turn drives the crank link 'a'. The crank link drives a main sprocket connected through a smaller sprocket attached to the spindle of main wheel of wheelchair. The chain drive delivers power from the crank to the main wheel in different gear ratios.
The chain velocity, V [15] is given by

$$V = Npn/60 \tag{7}$$

where, N: rpm of the sprocket in rpm, p= pitch of chain links in meters, n= number of teeth in the sprocket. The chain velocity, V=0.183 m/s.
The velocity of wheel chair is given as $V_w = 1 m/s$.

3.3 Disk Brake

The size of the rotor of the disk brake is chosen based on several factors such as torque required to stop the wheel, acceptable weight range and the amount necessary for safe operation. For a given friction force F between the brake pad and the rotor, the torque required to stop the wheel is dependent on the radius of the disk. The braking capacity of the disk depends on the contact area between the rotor and the brake pad. Disk with larger diameter can provide more braking power than the smaller diameter disk. Usually, bicycle disk brake rotors come in diameters of 160 mm, 180 mm and 203 mm. Considering the use of wheel chair is primarily restricted to level ground at low speeds and for minimum weight, the smallest of the available braking system will be chosen to minimize cost [15].
The frictional force between the ground and the wheel can be calculated using the principle of conservation of energy. Taking the mass of person 81 kg and the mass of wheel chair around 20 kg, and the velocity of the moving chair is 1m/s and assuming the brake is applied 1 m ahead of stopping, the work done by friction in stopping the moving chair. Equating the change in kinetic energy $\Delta K.E.$ and the frictional work done (W),

$$\Delta K.E. - W = 0 \tag{8}$$

$$(\tfrac{1}{2} mV^2 - 0) - F_w.s = 0$$

$$[\tfrac{1}{2}(81+20)\times 1^2 - 0]) - F_w \times 1 = 0$$

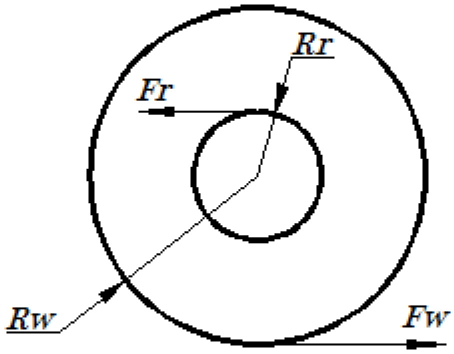

Figure 7 Rotor-pad frictional force and actuation

where, F_w is the frictional force between the ground and the wheel which is generally equal to 25.5 N. The radius of the wheel chair wheel is approximately equal to 0.3 m and the radius of the rotor is one half of 160 mm. The rotor-pad frictional force, F_r and the actuation force on wheel, F_w and the respective R_r=0.08m and the rotor pad radius, $R_w = 0.3m$, as shown in Figure (7).

force

$$F_r R_r + F_w R_w = 0 \tag{9}$$

$$F_r = -\frac{F_w R_w}{R_r} = -\frac{25.5 \times 0.3}{0.08} = 95.625N$$

Taking the coefficient of friction between the rotor pad and the disk on the wheel vary between 0.4 to 0.8, the normal to be applied through the rotor pad vary between $(95.625/0.8) \approx 120N$ and $(95.625/0.4) \approx 240N$. There is a mechanical advantage between the actual input force applied near the brake handle and the axial force applied on the disk. The mechanical advantage can be calculated based on the equilibrium of moments due to input force near the brake handle and the force on the disk. Taking that the force applied by hand is F_h and the force applied through the cable attached to the lever is F_r while the length of the lever where hand force is applied is $l_h = 80mm$ and the distance to the fulcrum to the point of attachment of cable is $l_c = 30mm$, then

$$F_h \times l_h = F_r \times l_c$$

$F_h = 45N$ and $90N$ corresponding to the two extreme conditions of friction. The mechanical advantage is obtained as $F_r / F_h = 2.67$.

3.4 Screw Lifting Mechanism

Power screws are generally used to transmit large axial forces with self-locking property. The screw is fixed in bearings restricting its axial movement.

The nuts assembled on the screw will have axial motion. These nuts in turn are connected a linkage attached at the bottom of the cushion of the wheelchair. Rotation of the screw causes the nuts to move axially causing the actuation of the linkage resulting raising or lowering the cushion. The condition for self-locking of the screw is satisfied through the relation [15].

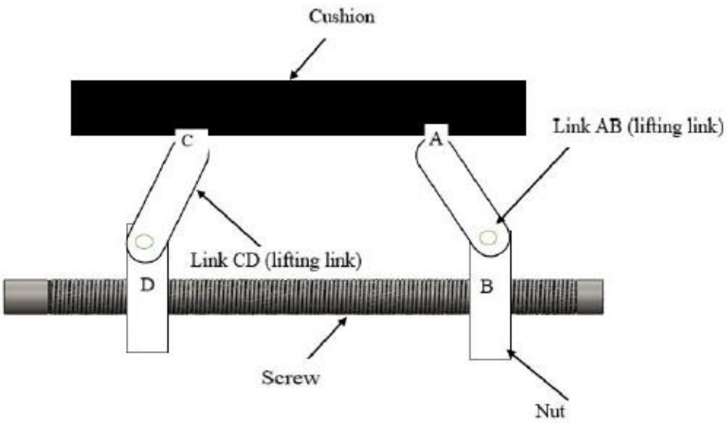

Figure 8 Screw lifting Mechanism

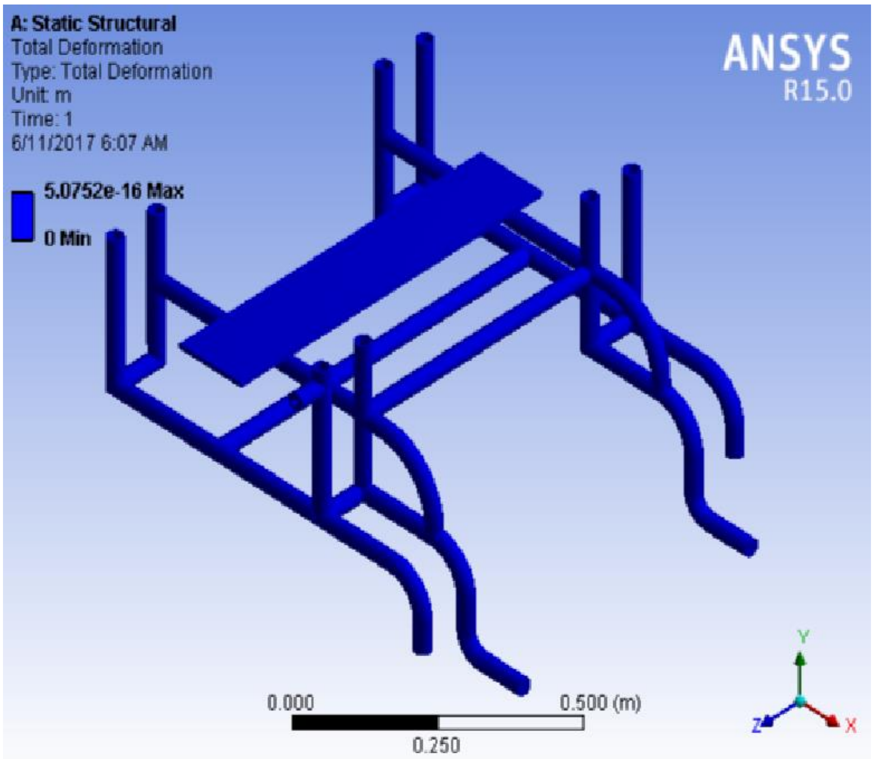

Figure 9 ANSYS analysis of wheelchair frame

$$f = \tan \lambda \tag{10}$$

where, f is coefficient of friction between the nut and the screw and λ is the lead angle of the screw.

3.5 Frame of Wheelchair

The frame of the wheel chair provides a foundation for mounting all the components. Size of the additional components shall be designed such that they can be accommodated on the fame of the selected wheel chair, which is generally a standard wheelchair. The fame must also support the load without deformation. The deformation of the frame the applied load is checked using ANSYS software as shown in Figure (9).

4 Conclusions

Velocity ratio is regulated through ratio of number of teeth on the driver and driven sprockets. The chain drive employed for propulsion has the provision for gear shifting to choose the speed. The propulsion, steering and braking systems can be easily detached or assembled on either left or right side of the standard wheelchair as per the requirement of the user. It allows steering and propulsion to be performed simultaneously. The hand lever is placed on the extended link of the crank-rocker four bar mechanism. Applying force at the extended lever provides mechanical advantage, thereby reduces the effort required by the user. Modification to the conventional wheelchair consists of a lever operated propulsion system in the forward or reverse directions depending on the choice of the user. Steering is accomplished by rotating the handle attached to a modified fork to rotate the castor. The disk brakes are operated by squeezing the brake handle and the lever. The lead screw with nuts and linkage arrangement causes raising or lowering of the cushion of the chair that facilitates easy transfer of the patient from chair to bed or stretcher and vice versa. This feature is very much important as it eliminates any possible strain or injury to the patient or the care giver.

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چکیده

این مقاله به اعمال تغییرات در طراحی یک صندلی چرخ‌دار می‌پردازد. به طوریکه با بهینه‌سازی سیستم پیشرانه و همچنین سیستم های تغییر مسیر و ترمز، امکان کنترل آنرا فقط توسط یک دست فراهم می‌سازد. عملکرد سیستم پیشرانه طرح پیشنهادی به کمک زنجیر و مکانیزمی چهارمیله‌ای است که توسط دستگیره اصلی به حرکت در می‌آیند. دیسکهای ترمزی که بر روی هر یک از چرخها متصل شده‌اند توسط یک اهرم ترمز که نزدیک به دستگیره پیشرانه اصلی است، عمل می‌کنند.

در این طرح یک اهرم قابل جدا شدن تعبیه شده که عملکرد آن توسط یک پیچ راهنماست و برای بازه وسیعی از مدلهای صندلی چرخدار قابل تنظیم است. می‌توان از مکانیزمی که توسط پیچ راهنما کار می‌کند برای تنظیم ارتفاع بالشتک کف صندلی و زاویه تکیه‌گاه پشتی آن استفاده کرد. لذا انتقال بیمار به تخت خواب یا برانکار تسهیل شود. طراحی مکانیزم صندلی چرخ‌دار بر اساس داده‌های ارگونومی مناسب برای انتقال مشتری به تخت‌خواب انجام شده است. نوآوری طرح پیشنهادی در بهره مکانیکی و نیاز به نیروی کمتر هنگام کاربرد و بهبود سرعت عملکرد به دلیل نسبت انتقال سرعت سیستم زنجیر است.