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Analysis and optimization of Lever Propelled Wheelchair

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***Abstract*—A wheelchair is a commonly used assistive device used by disabled people for mobility. An appropriate wheelchair gives them a sense of independence and encourages them to become productive members of the society. It gives them a feeling of belongingness and inclusion in the society. But for centuries now in India, there has been a clear vacuum of thoughts over a redesign of traditional wheelchairs.**

A new design of existing levered wheelchair is proposed here. This new design would increase the reach capabilities and social boundaries of disabled which inhibit the lives of the disabled day to day. The paper is divided into two parts. In the first part a comparative study has been done of push rim wheelchair and lever wheelchair. In the second part, Optimization of the lever wheelchair has been done.

The comparison has been done on various parameters such as peak velocity, average velocity, acceleration, retardation, Stroke frequency, Reduction in effort, Mechanical efficiency, Obstacle climbing ability, Turning radius, the distance travelled per stroke, Pressure cuts and burns caused during propelling the chair. Biomechanical testing is also done considering the heart rate and oxygen level consumption.This information can be used to determine the energy demand, which is intrinsically connected to a wheelchair's mechanical efficiency.

Feedback from test subjects was used for the optimization of the chair. The optimization mainly focus on the ergonomics and efficiency of design and for that the main emphasis is given on factors like the position of Lever-drive system, Configuration of wheel, chassis and Foot Rest. This optimized design would make the chair more efficient and easy to use by enabling the person to drive, steer, and stop without even touching the wheels, thus, eliminating the risk of friction burns and protecting the wrists and shoulders from repetitive stresses.

The analysis is done using software like ANSYS and CATIA and validation of results is conducted with the users and non-users of wheel chair.

Keywords—Lever propelled wheelchair, push rim wheelchair, comparison, optimization, ergonomics, and mechanical efficiency.

I. INTRODUCTION

India has about 20 million people with disabilities. Among the different types of disabilities, 11 million are locomotors disabled. The prevalence of locomotive disability is highest in the country –at 1,046 per 100,000 people in the rural areas and 901 per 100,000 people in the urban population [1].

A wheelchair (WC) is the catalyst to increased independence and social integration. An appropriate wheelchair can serve to reduce common problems such as pressure sores, the progression of deformities or contractures, and other secondary conditions such as spinal cord injuries.

The need of the hour is to provide less-resourced disabled people an ergonomic and efficient wheelchair. This would increase the social radius of such people.

In the first part of the paper, a comparative study has been done on lever propelled wheelchair (LWC) and push rim wheelchair based on various performance characteristics. The second part of the paper focuses on optimization of the various shortcomings of lever wheelchair to enhance its performance.

The propulsion of push rim wheelchair is the most painful task to do as the repeated usage for a prolonged time causes pain in hands and shoulders. The mechanical efficiency of hand-rim wheelchairs can be as low as 2-10% [2].

Hand rim wheelchair propulsion creates a high strain on the cardio respiratory and musculoskeletal systems, resulting in a high energy consumption, high heart rate, and low mechanical efficiency and on the long term, complaints related to anatomical structures of the upper limb. Inefficiency and stressful conditions related to this technique, especially for upper limbs, have been already reported in previous studies [3].The energy cost of everyday push rim wheelchair is fairly high [4]. Epidemiological studies have also shown a high prevalence of shoulder complaints in paraplegic and quadriplegic spinal cord injured (SCI) users [5,6]. The application of brakes induces friction burn and cuts in the hands of the user.

The ease of use and better efficiency provides an edge to lever propelled wheelchairs over push rim wheelchairs. The ergonomic design provides comfort to the user and makes the task less strenuous. The design is made such that it provides utmost ease when being operated in narrow places such as homes.This system is intended to provide a simpler means for obtaining an optimum mechanical advantage as compared to hand rim conventional propulsion. It supports good ergonomic postures and reduces the number of times a person has to drag the wheels.

Various factors which have been considered while optimization are the positioning of Lever-drive system, Configuration of wheel, Seating, Backrest, Chassis, Breaking and Foot Rest designing.The seat would be given a proper inclination.The optimized wheelchair comprises of all features necessary to provide safety while operation such as a proper braking system, seat belt, gripped handles etc. The material use for manufacturing is Chromoly which is of high strength and light weightwhich would ensure ease of manufacturing and a lower production cost. The design is such that the optimized wheelchair would require less maintenance and could be easily transported while the person is in transit. To make the design ergonomically sound adjustable arm rest, knee rest and foot rest are provided.The optimization is done keeping in mind the affordability of the product as this would be a major factor for the success of design in a country like India.

II. PART 1-TESTING

The various testing based on parameters like maximum speed, acceleration, Stroke frequency, Mechanical efficiency, Obstacle climbing ability, Turning radius , distance distances traveled per stroke , Pressure cuts and burns, heart rate and oxygen level consumption were done under similar conditions. Five users, 3 males and 2 females whose ages were approximately in the age group of 21-50 years, were the driver. Three out of five were non-wheelchair users.

- A human driver was used to perform the testing.
- Weights were added as per the need in order to bring the overall mass to 100kg.
- The backrest angle of the wheelchair was set to the most upright position.
- The wheelchair was run at maximum speed.
- The validation of results was conducted using both the wheel chair over different terrains like gravel, sand, grass, uneven ground, slope and wet surfaces using the necessary equipment as per the parameter to be measured.

The metabolic, maneuverability and usability tests were conducted. Recent studies have shown that the several physiological andmetabolic responses of wheelchair users are similar to able bodied person duringwheelchair exercise [7, 8]. Studies often use able-bodied subjects during metabolicwheelchair testing [9, 10, 11, and 12]. Using able-bodied subjects to test several different wheelchairs allowed results which were not biased by long term experience to a certain wheelchair type. Another reason that able-bodied subjects are often used in metabolic wheelchair research is due to their consistently high reliability or retest reliability for heart rate and VO_2 during wheelchair exercise. [13-15].

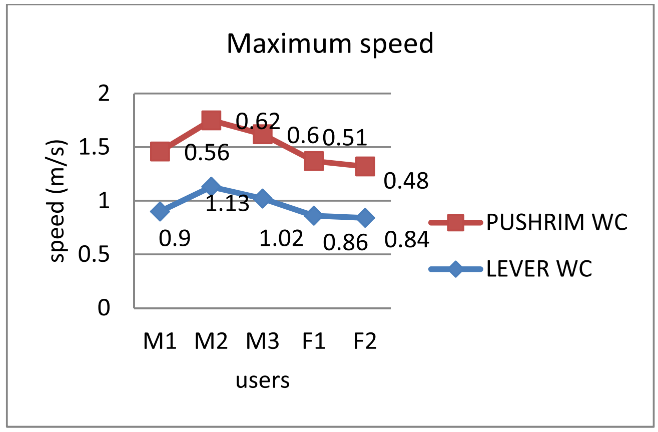
The wheelchair is tested in accordance to Section 6.2 of the Society of Automotive Engineers (SAE). The test methods and performance criteria are the same as those of ISO 10542-1 “Wheelchair tie down and occupant restraint systems – Part 1: Requirements and test methods for all systems,” and thus, compliance with SAE J2249 implies compliance with ISO 10542-1 [16].

A. *The methodologies used for various test conducted are mentioned as follows:*

1. *Maximum speed-*

The intention of this test was to determine the maximum speed of the wheelchair. The speed of the wheelchair can be varied by changing the position of gripping on the lever. The maximum speed was measured using a GPS based speedometer and recorded. The process was repeated thrice and average value for maximum speed was calculated.

CHART I

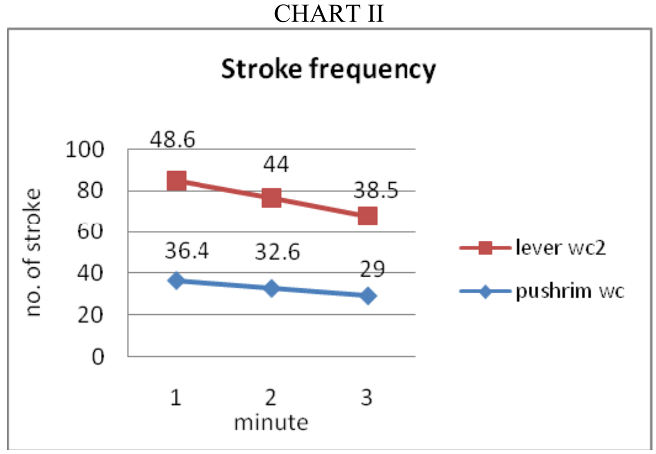


The average speed of lever wheelchair is 0.95 m/s which are 71.2 % more than push-rim wheelchair.

2. *Stroke frequency (cadence)-*

The number of movement of the lever was counted in a minute to find the stroke frequency. It basically represents the ease of propelling because the ease is directly proportional to cadence.

CHART II



The result data clearly represents that LWC is better than push rim WC.

3. *Obstacle climbing ability-*

The wheelchair was made to climb an obstacle from a standing start and from a run up distance of 0.5 meters. The height of the obstacle was increased by 2 mm each time until the wheelchair could no longer climb it.

TABLE I

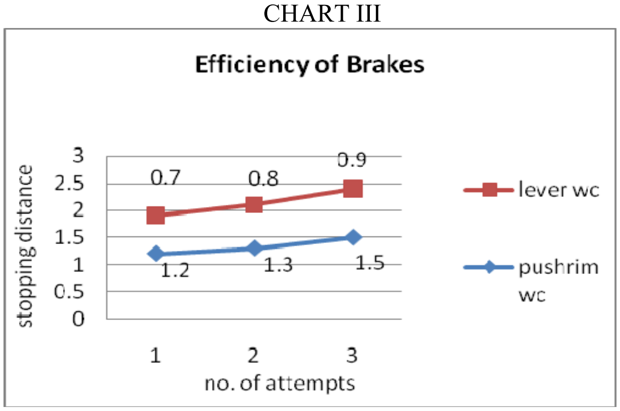
Push rim Wheelchair		Lever wheelchair	
Height of obstacle (in mm)	Ability to climb (by all 5 subjects)	Height of obstacle (in mm)	Ability to climb (by all 5 subjects)
13	Yes	15	Yes
15	Yes	17	Yes
17	Yes	19	Yes
19	No	21	No

The result from the test clearly represent that lever wheelchair can perform better in obstacle climbing as the torque is more in LWC.

4. *Efficiency of Brakes -*

The wheelchair was being operated at maximum speed. The break was applied and the distance that it travelled after the application of break was measured. The process was repeated thrice to find the average value of breaking distance.

CHART III



The result data clearly represent that Lever WC breaks are more effective than pushrim WC.

5. ***Maneuverability-***

In order to make the lever wheelchair equally effective in narrow areas such as homes, workplaces, hotels etc. and making the remote corners completely accessible to the wheelchair user, the turning space plays a vital role. To measure it a narrow passage was created and was further narrowed until the wheelchair was unable to turn around it.

TABLE II

USER	Minimum turning radius(Push rim)	Minimum turning radius(Lever)
M1.	0.6m	1.1m
M2.	0.7m	1.1m
M3.	0.8m	1.2m
F1.	1m	1.4m
F2.	1.1m	1.5m
Average	0.8m	1.3m

Average Minimum turning radius for push-rim is 0.8m and for lever wheelchair is 1.3m, so the lever propelled wheelchair isless maneuverable than push-rim wheelchair.

6. *Power efficiency -*

During the testing, the metabolic demand was measured in terms of heart rate (HR). The heart rate of the user was continuously recorded during the propulsion. A Heart rate monitor (Polar FT1 Heart Rate watch) was attached to user's wrist. The readings of heart rate monitor and speedometer (attached to the wheelchair) was recorded using a video camera pointed at counter.

$$D = \text{distance travelled/total distance} \quad (1)$$

Now, P signifies the power efficiency (Newton), which is defined as

$$P = \mu mg/HR^* \quad (2)$$

$$HR^* = HR_{current} / HR_{resting} \quad (3)$$

Where

μ= coefficient of rolling resistance,(μ_{roll}, ranging from 0.005 to 0.5 [17, 18])

m= total mass of the user and wheelchair,

g= acceleration due to gravity,

V= velocity of wheelchair,

HR= Heart rate

Here, μmg is approximately mechanical output power and HR* may be used as the measure of physical exertion.

TABLE III

Subject ID	V avg Lever	V avg Push-rim	Distance	Terrain	$P^*_{lever} / P^*_{pushrim}$
M1	1.20	1.17	1061	Dirt road	1.10
M2	1.03	2.33	1021	Tarmac +	0.82
M3	1.0	1.33	896	Hilly, rough	1.25
F1	0.12	0.07	21	Flat, smooth	1.04
F2	0.17	0.29	45	Dirt road	1.77

The result data clearly represent that the power efficiency of Lever WC is greater than the power efficiency of pushrim WC except for the subject M2.

7. *Pressure-cuts and burns-*

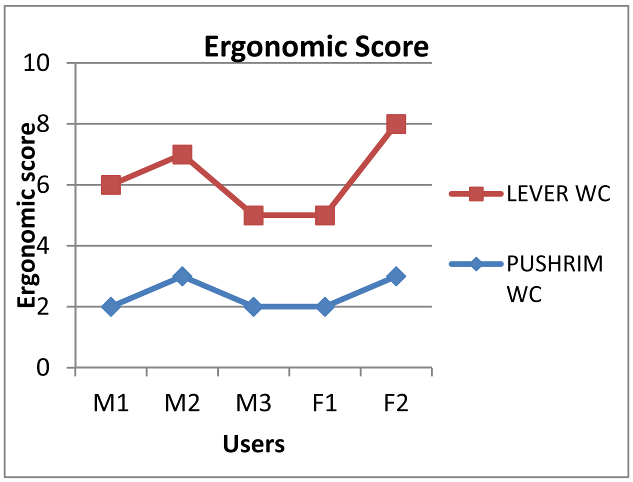
The friction produced by pushrim wheelchair causes friction burns and pressure cuts on the hand of the user. The feedback was taken from the users while testing and hands for respective users were visually inspected. Levered wheelchair produces negligible cuts or burns.

8. Usability testing-

Usability refers to the level of comfort offered by a wheelchair to the user making it better and easier to use. Although a wheelchair may be highly maneuverable or mechanically efficient it is not practically viable to use if it is uncomfortable or complicated to use.

For testing, the users were asked to scale the performance of the respective wheelchairs over different terrains such as concrete, grassy, tiles and muddy after all the tests were conducted. The scaling was done on a scale of 5; 1being very bad to 5 being very good.

CHART IV

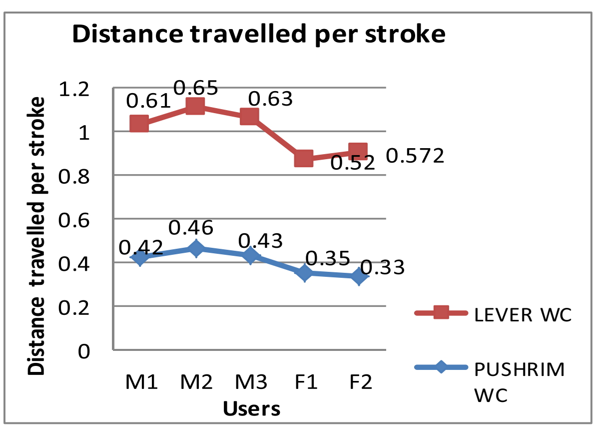


9. Distance travelled per stroke-

The distance travelled per stroke can be calculated by two methods. Firstly, the distance can be measured for each stroke individually. Else, the total distance travelled may be divided by the number of strokes required to cover that distance.

We have used the former one as it is has higher accuracy.

CHART V

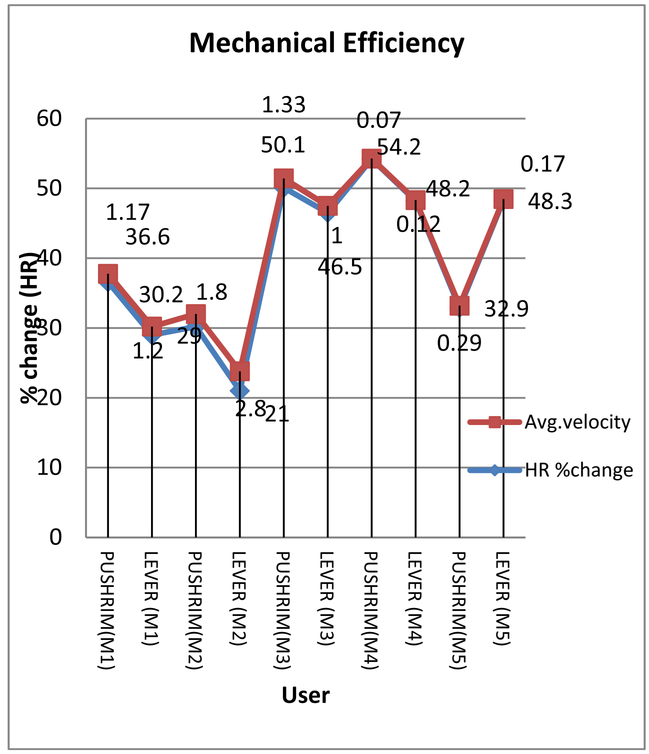


The result clearly depicts that LWC distance per stroke is 43.2% more than push-rim wheelchair.

10. Mechanical Efficiency (Heart rate with respect to Average speed) –

Metabolic studies of wheelchair activity often focus on oxygen consumption and heart rate [19-20].This information is used to determine the energy demand, which is intrinsically connected to a wheelchair's mechanical efficiency. The users were directed to operate the wheelchairs as per their ease and comfort during the testing. The heart rate was measured before and after the completion of the test.The efficiency of lwc is found to be 48% more than that of pushrim .

CHART VI



III. Part 2-Optimization

The comparison of lever wheelchair and push rim wheelchair on various parameters mentioned above clearly indicate the competence of lever wheelchair over the push rim. But the present design of lever wheelchair still requires some modifications for the optimum utilization of the concept. For the further development of this LWC, feedbacks were taken by its daily users and by people operating it during the various testing conducted. The problems indicated by them were jotted down and research was carried to improve it. The optimization mainly focus on the ergonomics and efficiency of design and for that the main emphasis was given on factors like the position of Lever-drive system, Configuration of wheel, Seating, Backrest, chassis, Breaking ,wheel camber and Foot Rest. Optimization was done by using the research data available by various researches conducted already and on the other hand various new methods and softwares were employed to get the best possible design.

Extensive testing of lever propelled wheelchairs revealed the following problems:

•The small castors wheels at the front of the wheelchair provided insufficient obstacle climbing ability.
•The frame is relatively heavier declining the performance
•There is no reverse drive in the current design which is a major drawback as LWC may getstruck.
•Poor enunciation and rigid frames cause standard wheelchairs to lift off the ground on uneven obstacles.
•The brakes are applied using a metal part which comes in contact with the tire and rubber. This causes the rubber tires to wear and eventually rupture. The brakes are inadequate to control the downhill travel safely.
The position of the large rear wheels might cause tipping backwards when climbing the slopes and would requires great skills.
The design was reconsidered entirely except the basic lever propulsion system for better performance, comfort, safety, accessibility strength, and durability.
The optimization was done based on following parameters-

1. Lever-drive system –
   - levers length
   - the position of axis of rotation
2. Configuration of wheel
3. Seat surface height and inclination of seat
4. Backrest height and its angle
5. Basic chassis design
6. Break design
7. Foot Rest design
8. Wheel camber

Method for optimization –

The optimized values for each parameter mentioned above are determined separately.

***1.** For lever-drive system-*

The variation in lever length and its axis of rotation directly affects the mechanical efficiency of the wheelchairs and the ease with which the user may exert force.
These optimizations were done in correspondence to a human shoulder joint position and gearing needed.
The LWC incorporated a multi speed, fixed gear ratio drive train.

Fig. 1 Changing hand position on the levers varies mechanical advantage of the drive train

Unlike most gear trains, which are operated in varied states of multiple sprocket cassete to obtain multiple ratios, the LWC's drive train exists in only one state i.e. only one combination. If more torque at the wheel is needed to climb a hill, the user simply slides his hands up the levers and away from the pivots, as shown in Fig. 3. If more speed is required, the user moves his hands closer to the lever pivots, achieving a greater angular deflection with every push stroke. The relationship between chair speed and hand speed is represented by Equation 4

$$\frac{V_{Chair}}{V_{Hand}} = \frac{R_W}{L} \qquad (4)$$

Where,

V_{Chair} is the chair velocity,
V_{Hand} is the user's hand velocity,
R_W is the wheel radius,
L is the lever length.

The LWC is powered by pushing the levers forward. On the return (pull) stroke, bicycle freewheels on the rear hubs allow the chains to freely ratchet and the levers to return to the starting position of the push stroke.
The individual biomechanical characteristics of Human anthropometry (ergonomics) were also considered. The nature of the propelling system used in these wheelchairs is already well examined from various points of interest such as – propelling arm move pattern [21], limb joint dynamics [22], biomechanics and physiology of the propulsion process [23]. Yet there is scope for improvements which if sufficiently developed, may significantly improve the quality of motion and thus quality of life of handicapped people. [24–25]
Two methods employed for getting the optimum dimensions are:

- Mocking the process virtually by using Catia-Rula analysis.
- Analytical optimization method which was based on experimental data. Validation of results was done by mocking the process by creating the spatial arrangement of the seat and axis of lever and a lever in workshop.

*Analytical Method**:***

A. For lever length optimization:

The length of the lever plays a crucial role for proper selection of maximum torque and maximum speed value. The value of upper body pushing power is adapted from result of Woude, [26] and was calculated to be 19.6W with a pushing force of 58N and hand velocity of 0.33m/s. Testing was done to find the gear ratio system for the LWC which would yield highest efficiency with relatively low exertion. The value of power output was used in Equation 4 to calculate the attainable velocity for long-duration travel on a variety of terrains, neglecting efficiency losses in the drive train.

$$P_{Human} = P_{Drag} + P_{Rolling} + P_{Gravity} \quad (5)$$
$$= (1/2)C_D \rho_{air} A (V_{Chair})^3 + mg (V_{Chair}) [\mu_{roll} \cos\theta + \sin\theta]$$

Values in Equation 5 were $C_D = 1$ [Autodesk Simulation CFD] [17], $\rho_{air} = 1.2kg/m^3$, A=0.6m^2 [Autodesk Simulation CFD], rider + chair mass, m = 75kg, and g = 9.81m/s^2. Road surfaces material in developing countries vary from tarmac to gravel, mud or sand and the corresponding rolling friction coefficients, μ_{roll}, range from 0.005 to 0.5 [17, 18]. Slope angles, θ, used in this analysis were varied between 0° and 40°, just beyond the backwards tipping angle of the lever wheelchair.

Using Equation 5 with V_{Hand} = 0.38m/s and the V_{Chair} data generated from Equation 5, the required lever length at each combination of rolling resistance and angle was calculated. These data were compared to lever lengths that we could comfortably grasp, which were measured to be having a maximum of L = 84cm to a minimum of L = 24cm.For common road conditions, with rolling friction ranging from 0.01 to 0.1 (approximately tarmac to gravel) and slopes up to 5° (1:11 rise), the rider can propel himself at maximum efficiency.

On rough surfaces such as sand or steep hill, the rider would have to compromise with speed in order to achieve high torque at the wheels. Hence, the chair velocity will be very small making the value of V_{chair} negligible and reducing Equation 5 to Equation 6,

$$P_{human} = F_{Resist} * V_{chair}$$

$$F_{Resist} = mg[\mu_{roll}\cos\theta + \sin\theta] \quad (6)$$

Where, F_{Resist} is the total resistance force acting on the chair. Rearranging Equation 4 for force instead of speed transfer, and neglecting drive train efficiency, yields Equation 7,

$$F_{Resist}/F_{Hand} = L/R_w \quad (7)$$

Where F_{Hand} is the pushing force exerted on the levers.

By combining Equations 6 and 7, the required lever length for any terrain condition can be obtained as a function of F_{Hand}. Maximum attainable pushing force was determined through US military tests on aircraft control sticks [27]–an interface geometrically similar to the LWC levers. For 50percentile of the males in the population, this force was measured to be 356N. Using F_{Hand}=356N, the required lever length at every plausible operating point was calculated for different values of μ_{roll} and θ.

The results shows that one set of levers, which can be grasped between 22cm to 86cm from the pivot, will enable an LWC rider to travel on virtually any terrain.

B. The position of axis of rotation

A spatial arrangement of non-integrated wheelchair parts was used to check the position for lever for different value of loads. For this seat, wheel, lever and its axis were assembled and the test was proceeded by applying loads on the lever (simulating resistance to motion) for the given motion conditions

The method consisted of measuring the human fatigue caused by propelling a lever wheelchair with unconstrained spatial arrangement consisting of a wheel assembly and lever attached to it.

The following simplifying assumptions were made to calculate the lever length :

- The velocity of lever motion was not taken into consideration.
- The development of the fatigue process in time doesn't change the optimal values of analyzed parameters.
- The solutions presented here for optimization are independent of load value on the lever.

So the general outline is that to minimize the physical strain such that the human arm should employ push force in the position for which the value of pushforce is maximum.

Now considering the above assumption and the layout we can estimate the maximum energy that a human arm can blow according to the general equation 8.

$$W = F \cdot s = \int_C F \cdot ds \quad (8)$$

Where W =energy blown by arm during a single push or pull stroke;

F =arm push force vector (varies with arm position);

s = hand displacement vector;

C= path traversed by the human hand;

ds =position vector.

However force is not unidirectional. The F changes with lever motion as the force is applied on the lever. The trajectory for integration of work done can be considered as an arc of circle. The relation between both the parameters can be obtained by using regression analysis which is an experimental optimization method. The value for the average force was taken 63.2 N [28]. For minimum work the position of axis of rotation can be found out easily. Lever length can be calculated from the maximum torque requirement for the slope climbing configuration of wheel.

RULA Analysis:

The lever length and position of axis is analyzed and crosschecked by the ergonomics part of Catia V5 i.e. Human activity analysis. In which a manikin of dimension 50 percentile male was placed on the wheelchair for RULA.

RULA (Rapid Upper Limb Assessment Analysis) analysis describes the stress developed on various parts of the body of driver and gives a score known as RULA score which gives a value out of 7.

The lesser is the score, lesser is the stress developed. It is shown by different color tones like green, yellow and red.

Various positions of lever were tried to get the lowest possible stress and maximum score.All the final result for both left and right RULA analysis gives a good score which depicts the stress generation on human body is minimum and hence the driver feels comfortable without any strain

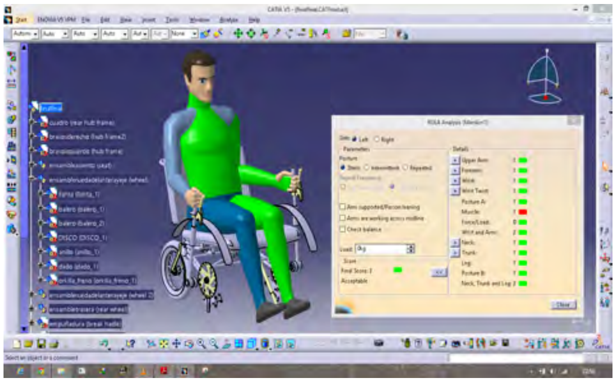


Fig.2 Left RULA analysis on catia v5

Usually in most of the wheel chair rear wheel propulsion is employed such that when we are propelling it we effectively push it against our body weight. If we push hard enough, we might lift our self out of the chair. That limits how effectively we can push it. But this does not occur with front wheel propulsion.

We have employed front wheel propulsion due to following reasons:

- The reaction to pushing is resisted by the back seat which is relatively at a greater distance in front wheel propulsion.
- Foot positioning will also be easier, because there are no front casters to interfere with foot placement. Therefore, the front-wheel drive design can help to keep the feet positioned closer to the body, and can also provide an aid to keep the seat-to-floor height low. This in turn lowers the center of gravity and increases the stability drastically.
- Front wheel drive wheelchairs are the best performers in sandy terrain.
- The large front wheels are first to encounter the obstacles which are usually bigger than small caster wheel and they pull the rest of the wheelchair over thebut in rear-wheel drives, the front casters encounters first. Moreover, a rear-wheel drive means the drive wheels are pushing the front casters over obstacles. Pushing is harder than pulling, so the rear-wheel drives aren’t as efficient for climbing the obstacles as front-wheel drives are.
- The reason that this concept wasn’t implemented before is due to the dynamic instability and the wheelchair could fishtail or spin out when cornering, making it very hard to control. This was caused due to the presence of free rotating castors and few years earlier it was difficult to make a front wheel propelled wheel chair run straight.

  The solution for this problem lies in the design itself i.e. providing a larger caster angle for the castor wheel and orienting the center of gravity of the wheelchair more on the rear caster wheel. This would increase the stability of single rear castor wheel stability and eliminate the problem of fishtailing and spin out at cornering.

3. *Reversible Drive-*

One of the major problem found in the LWC was that it could not revese.So it was the main challenge to incorporate a reverse drive in new design to make it better. So a new drive with a innovative mechanism is designed to make it reversible which is actuated with the help of small lever integrated in the handle..

4. *Basic chassis design-*

It was designed on the basis of two criteria -

- Minimum material usage which could accommodate all the subassemblies and mounting of parts for lighter and cheaper design.
- Strength of wheelchair must be able to safely execute without any failure in its entire tenure.
- The ratio of weight to factor of safety is thefinal criteria considered for opting for the apt chassis design.

The material used is Chromoly (AISI 4130) as it is inexpensive, easy to work, readily available. To check the strength of chassis FEA (Finite Element Analysis) was done using ANSYS and the result found were satisfactory.

It is recommended that each country develop its own wheelchair standards to ensure a reasonable quality, for instance by using the ISO 7176 series of standards as a basis.

5. *Foot rest design–*

It is designed on the basis of following criteria-

a. Adjustable footrest-

The height of the footrest should be adjustable. The footplate reduces pressure on the user's seat and puts the user in a comfortable sitting posture. Sufficient ground clearance needs to be maintained to prevent the footrest hitting the obstacles.

b. Removable footrests –

- It allows a user to get closer to surfaces to which the user wishes to transfer.
- It allows a user to get closer to surfaces and increase his accessibility.
- For transfersfrom wheelchair to other place, removable footrests are needed to get out of the way of the user's feet.

6. *Camber–*

The existing lever wheelchair does not have camber but might increase lateral stability of the wheelchair.

It was selected on the basis of following criteria-

- The greater the camber the easier it is to turn the wheelchair.

- The lateral stability of the wheelchair increases as tha camber increases.
- For the new design 8 degree camber is used to counter the fishtail effect and make the design more stable for all terrains.

Fig.3 final assembly rendered image of proposed optimized wheelchair

IV. CONCLUSION

The lever wheelchair proved to be better in almost all the testing parameters in comparison to pushrim wheelchair. But there is always a possibility for improvement and formulation of a better design that aims to increase the efficiency and user comfort.The new proposed design has been considered on all the parameters and after ample analysis and research, the design is improved on the aforementioned parameters.

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[28] A kinetic analysis of manual wheelchair propulsion during start-up on select indoor and outdoor surfaces.Alicia M. Koontz, PhD, RET; 1–3* Rory A. Cooper, PhD;1–4 Michael L. Boninger, MD;1–4 Yusheng Yang, MA;1,4 Bradley G. Impink, BS; 1–2 Lucas H. V. van der Woude, PhD3, 5