Supported by tetfund TERTIARY EDUCATION TRUST FUND

Theoretical Analysis of the Required Force of a Wheelchair Propulsion by Nigerian Adult Paraplegic

[1]Ashiedu Festus Ifeanyi and [2]Nwaoha Thaddeus Chidi
[1]Mechanical Engineering Department, Federal University of Petroleum Resources, Effurun, Delta State. Nigeria

[2]Marine Engineering Department, Federal University of Petroleum Resources, Effurun, Nigeria.

E-mail: ashiedu.ifeanyi@fupre.edu.ng,nwaoha.thaddeus@fupre.edu.ng
Received: December 13, 2021 Accepted: February 20, 2022

ABSTRACT Paraplegics in Nigeria are faced with multiple challenges that affects their emotional, physical, social and economic lifestyle. Based on these challenges, they are seen as second class citizens in their own country. This paper therefore seeks to address their mobility challenges, using mathematical models to ascertain the required force needed to propel an ergonomic friendly wheelchair through a ramp to points of service provisions. If this is done, life will become meaningful to them once again. The model developed using mathematical and scientific knowledge was such that the force required to access points of service provisions using a manually propelled mobility aids are estimated. The result of our findings showed that the average force required to propel an ergonomic friendly wheelchair to points of service provision ranges from 1354 N to 1425 N for female and male adults' paraplegics respectively. This force is capable of developing extra muscular disorders. These disorders arose as a result of repetitive propulsion of these wheelchairs on inclined plane daily. The magnitude of the force required to be overcome, again is capable of creating epidemiological conditions that affects these sets of persons negatively. Our paper therefore concludes that an autonomous mobility aid capable of taking paraplegics to points of service provisions through ramps and other inclusive designs is recommended for these groups of persons whose self-esteem has already been tampered with. When this is done, Paraplegics will be fully integrated into the society thereby contributing positively to the economic, political and social growth of the nation, as against their usual ways of soliciting for arms in our highways, Churches and other public places.

Key words- Paraplegics, Mobility, Ramps, Force challenges.

Introduction

Nigeria today is bedeviled with so many ills such as banditry, kidnapping, robbery, corruption and many others. These social ills are results of youth's unemployment, inadequate social welfare packages for the masses and bad governance among our political leaders. Again, lack of adequate infrastructural facilities in private and public buildings constitute yet another self-induced trauma among the abled and the disabled bodied men and women. In all these, the most affected group of persons are the persons suffering from lower limb deformity, otherwise referred to as Paraplegics. These Paraplegics who have no means of livelihood resort to self-help by assisting criminal elements in hiding dangerous equipment and weapons used for most operations in the country. Again, since they constitute more than 70 % of beggars in our major streets, they offer useful information to criminals in return for cash rewards. All these in addition to paraplegic mobility challenges compounds the economic status of Nigeria as a nation. However, for our nation to exit from these myriads of challenges, the problems have to be tackled head on. This can be done by creating opportunities that will enable paraplegics and other disabled persons to compete favorably with abled-bodied men in terms of employment, entrepreneurial training and other spheres of life.

This paper therefore seeks to find a lasting solution to the mobility and accessibility challenges faced by paraplegics in Nigeria by way of policy frame work. If this is properly done, practiced and implemented to the later, paraplegics in Nigeria will now work effectively in their chosen vocation and contribute their quota meaningfully to the growth of our nation Nigeria. Many scholars have worked on the mobility needs of paraplegics both at home and abroad. Some of the notable ones include Ashiedu and Igboanugo (2010). The paper highlighted the need for government and policy makers at all level to develop a paraplegic centricity mobility aid which will address the mobility challenges of these set of persons in our society. Similarly, Ayodeji *et.al*, (2008a) developed a CAD software for the design of mobility aid for paraplegics. Again, the anthropometric data of Nigerian adult paraplegics were carried out for the purpose of carrying out a pleasurable product design and development among others (Ayodeji et.al 2008b).

Ebrahimi *et.al* (2016) carried out a review on the influence of physical activities on the quality of life of persons suffering with lower limb deformity and the disabled individuals. The paper emphasized on the importance of biomechanical aspect of wheelchair design. The paper named wheelchair propulsion, assistive technologies and prevention of pressure ulcers among others. In their view, if these aspects of wheelchair design are given priority that it deserves by experts and designers of pleasurable products, paraplegics, spinal cord patients and other disabled persons will enjoy enhanced physical activities; also, their social life will improve tremendously. When this is done, they will be productive to the society instead of being a burden to the same society. This same view was corroborated by Ravenek *et.al*.(2012).

Similarly, Kawanishi *et.al*.(2013) and Vander wonde *et.al* (2006) in their separate papers worked on the functional autonomy of people with lower limb deformity in terms of mobility. The papers encourage inclusive design policy implementation at all levels to aid and assist these class of persons with little or no assistance in accessing their points of service provisions. By this they will be productive to the entire nation, have improved self-esteem among others. Emphasis on the use of self-energy and body weight by paraplegics to increase the posture transformation capabilities in terms of costs and user friendliness to overcome their challenges was opined by Guatam *et.al* (2019). The paper added that the modular wheelchair was designed to allow the disabled persons use his or her own body weight and energy to actuate between sitting positions to standing positions without relying on care givers and other electrical devices.

Goher (2013), pointed out that movement constrained by wheelchair design among paraplegics has a long lasting effect on their health. The paper quoted some past studies that concluded that increased body movement and change in postures provide several health benefits such as reducing the risk of muscle spacisity, muscle contractures, and osteoporosis. This finding was corroborated by Arva *et.al* (2009), and Oden and Knutssun (1981).

In a related study, Lizama *et.al* (1992) proposed the use of hydraulic devices to assist people with lower limb deformity. The paper pointed out that each user can convert sitting position to standing position by using a hydraulic jack attached to the wheelchair. This hydraulic jack again can lower the patients to its sitting positions as the need arose. This contribution to the plight of paraplegics was supported by Kamnik and Bajd (2004).

Methodology

The sketch in figure 1 represents the state of a wheelchair climbing an inclined plane. For the purpose of this work, the angle the plane makes with the horizontal is denoted by theta (θ).

Figure 1 shows the diagram of the motion of a body (wheelchair) moving up an inclined plane.

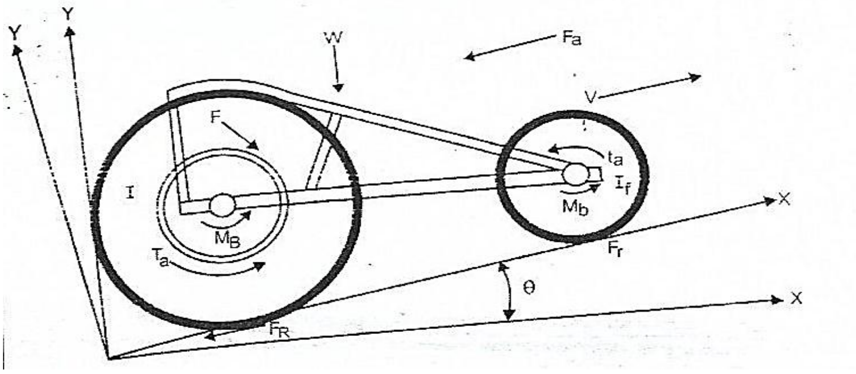

Figure 1: Block diagram of wheelchair propulsion on an inclined plane.

Using the free body diagram in figure 1, the forces can be resolved into the vertical and the horizontal components. The weight of the subject and the wheelchair acting vertically downward is represented by$W$. F_a is the air resistance, V is the velocity of the wheelchair along the inclined plane, M_B and M_b are the bearing resistances for the rear and front wheels respectively. F_R is the resistance offered the rear tyre up the inclined plane and F_r the resistance offered the front tire during motion. The angle of inclination is represented by θ.

Summing the forces in the X – direction, we have

$\sum F_X = 0$

$F\ cos\theta - R\ sin\theta = 0$

1

Where, w = is the weight of the wheelchair and the occupants acting vertically downwards.

Since $Sin\theta = \frac{BC}{AC}$ then,

$F - WSin\theta = 0$

2

Similarly, sum of forces along the y-axis is given by

$\sum F_y = 0$

Therefore,

$-W + R\ cos\theta + F\ sin\theta = 0$

3

Hence,

$R\ cos\theta + F\ sin\theta = W$

If the effects of friction is assumed to be negligible, and the wheelchair is moving up the inclined plane, then

$W = F$ Hence,

$MgSin\theta = Ma$

$gSin\theta = a$

Since the frictional effect is not negligible, it therefore follows that

$F - WSin\theta = Ma$

The force acting against the motion of the wheelchair due to the weight of the wheelchair and the weight of the individual is given by

$F = Ma$

4

The resistance due to air power is expressed by equation 5 as

$F_a = CV^2$

5

Where

C = coefficient of air drag

V = air velocity, and

F_a = air resistance

But,

$C = \frac{\ell AC_D}{2}$

Similarly, the effect of inertia on the front and the back wheel which is inversely proportional to the radius of the wheels is given by

$\frac{I_a}{R}$ and $\frac{I_b}{r}$
6
Where,
R = radius of the bigger wheel
r = radius of the smaller wheel
The bearing resistance up the inclined plane for the rear and front wheel is given by
$\frac{M_B}{r_{ax}}$ and $\frac{M_b}{r_{axf}}$
7
The rolling resistances offered by the two tires is represented by
R_R and r_r
8
The resistance offered by the weight of the individual with respect to the grade angle is given by
$WSin\theta(x)$
9
Summing all the resistances gives the total resistance suffered up an incline plane
$F\left(\frac{R}{r_{pr}}\right) = M\dot{v} + \frac{I_{ar}}{R} + \frac{I_{af}}{r} + F_a \frac{M_b}{r_{axf}} + \frac{M_B}{r_{ax}} + F_R + F_r + WSin\theta(x)$ 10
*Recall that the total resistance at the rear wheel is directly proportional to the resistance offered by the fraction of the total weight and the grade angle, but inversely proportional to the radius of the wheel.
$F_r \alpha W_R Cos(x)$ and $F_R \alpha \frac{1}{R}$
11
Also, the same condition applies to the front wheel
$F_r \alpha W_r Cos\theta(x)$ and $F_r \alpha \frac{1}{r}$
12
Introducing the constant of proportionality $b_R and b_r$ respectively, we have
$F_R = \frac{W_R b_R Cos\theta(x)}{R}$, And
$F_r = \frac{W_r b_r Cos\theta(x)}{r}$
13
Substituting equation 13 into equation 10 we have
$F\left(\frac{R}{r_{pr}}\right) = M\dot{v} + \frac{I_{ar}}{R} + \frac{I_{af}}{r} + Cv^2 + \frac{M_b}{r_{axf}} + \frac{M_B}{r_{ax}} + \frac{W_R b_R Cos\theta(x)}{R} + \frac{W_r b_r Cos\theta(x)}{r} + WSin\theta(x)$ 14

Re arranging equation 14
$F\left(\frac{R}{r_{pr}}\right) = (M + \frac{I_{ar}}{R} + \frac{I_{af}}{r})\dot{v} + Cv^2 + \frac{M_b}{r_{axf}} + \frac{M_B}{r_{ax}} + \left(\frac{W_R b_R}{R} + \frac{W_r b_r}{r}\right) Cos\theta(x) + WSin\theta(x)$ 15
At this stage, we assume that the bearing resistances are proportional to the velocity of the wheelchair and that we can combine them for mathematical tractability. Then,
$(\frac{M_B}{r_{ax}} + \frac{M_b}{r_{axf}})\alpha v$
Introducing the constant of proportionality
$K_3 v = \left(\frac{M_B}{r_{ax}} + \frac{M_b}{r_{axf}}\right)$
16
Substituting equation 15 into equation 16 gives
$F\left(\frac{R}{r_{ar}}\right) = \left(M + \frac{I_r}{R} + \frac{I_f}{r}\right)\dot{v} + Cv^2 + K_3 v + \left(\frac{W_R b_R}{R} + \frac{W_r b_r}{r}\right)\cos\theta(x) + WSin\theta(x)$ 17
By substituting $v = \frac{dx}{dt} = \dot{x}$ into equation 16, it follows that
$F\left(\frac{R}{r_{ar}}\right) = \left(M + \frac{I_r}{R} + \frac{I_f}{r}\right)\frac{d\dot{x}}{dt} + C\frac{d\dot{x}^2}{dt} + K_3\frac{dx}{dt} + \left(\frac{W_R b_R}{R} + \frac{W_r b_r}{r}\right)\cos\theta(x) + WSin\theta(x)$
Similarly, $\dot{x} = \frac{d^1x}{dt^2}$, also $\dot{v} = \ddot{x}, v^2 = \dot{x}^2, v = \dot{x}$
18
Assuming that the various resistances are proportional to the velocity of the wheelchair, then
$K_1 = \left(M + \frac{I_r}{R} + \frac{I_f}{r}\right), K_2 = C, K_3 = \left(\frac{M_B}{r_{ax}} + \frac{M_b}{r_{axf}}\right), K_4 = \left(\frac{W_R b_R}{R} + \frac{W_r b_r}{r}\right) and K_5 = (w)$ 19
Substituting equation 18 into equation 16 gives
$F = K_1\ddot{x} + K_2\dot{x}^2 + K_3\dot{x} + K_4 \cos\theta(x) + K_5 \sin\theta(x)$
20
Equation 20 is a non-linear differential equation which describes the interaction of a moving wheelchair with the environment.
If the wheelchair operates without the influence of the environment (no slope, no air resistant), then equation 20 reduces to
$F = K_1\ddot{x} + K_2\dot{x}^2 + K_3\dot{x} + K_4$
21
If torque is the ability of a rotating body to overcome turning resistances, then
$T \alpha I\dot{w}$
As usual, summing all the torques acting on the wheelchair, we have
For the rear wheel, $T = I\dot{w}$
22
For the front wheel, $T = I_f + \dot{w}_f$
23
Torque due to air resistance, $F_a = Cw^2$
24
If the moment of rolling resistance and the coefficient of rolling resistance are equal, then
$F_R R = W_R b_R$
25
Summing the total torque
$T = I\dot{w} + I_f \dot{w}_f + F_a + M_b + F_R R + T(w,z,t)$
26
Substituting air resistance into equation 26, also assume no slip condition
Then, $w_f = \frac{R}{r}$
$T = \left(I + \frac{I_f R}{r_f}\right)\dot{\omega} + C\dot{\omega}^2 + \dot{M}_b + F_R R + T(w,z,t)$
27
If
$K_1 = \left(I + \frac{I_f}{r_f}\right)\dot{\omega}, K_2 = C, K_3 = b_R, K_4 = M_B$
It follows that
$T_{total} = K_1\dot{\omega} + K_2\dot{\omega}^2 + K_3\omega + K_4 + T(w,z,t)$
28
Assuming no slip condition between the rollers and the back wheel, then
$\omega = \frac{v}{R} = \frac{(\frac{\partial x}{\partial T})}{R}$
$= \frac{\dot{x}}{R}, \ddot{x} = \dot{v} = \frac{\partial^2 x}{\partial t^2}, z = x$
Substituting these expressions into equation 28, we have
$T_{total} = K_1\frac{v}{R} + K_2(\frac{v}{R})^2 + K_3(\frac{v}{R}) + K_4$
$T_{total} = K_1\left(\frac{\dot{x}}{R} \times \frac{R}{1}\right) + K_2(\frac{\dot{x}}{R} \times \frac{R}{1})^2 + K_3\left(\frac{\dot{x}}{R} \times \frac{R}{1}\right) + K_4 + T(w,z,t)$ 29
It therefore follows that

$T_{total} = K_1\ddot{x} + K_2\dot{x}^{2} + K_3\dot{x} + K_4 + T(\dot{x}, x, t)$
30

Comparing equations 20 and 30, the coefficient of the equations must be set to be equal and opposite. (Newton's 3^{rd} law of motion)

Hence

$F = K_1\ddot{x} + K_2\dot{x}^{2} + K_3\dot{x} + K_4\, cos\theta(x) +$
$K_5\, sin\theta(x) = K_1\ddot{x} + K_2\dot{x}^{2} + K_3\dot{x} + K_4 + T(\dot{x}, x, t)$

At this point, we assume the following physical restrictions

$K_2 = c \neq C = K_2$

$K_3 = \frac{M_B}{r_{ax}} \neq \left(\frac{M_B}{r_{ax}} + \frac{M_b}{r_{axf}}\right) = K_3$

$K_4 = (W_R b_R + W_r b_r) \neq (W_R b_R) = K_4$
31

Satisfying the inequalities

$k_1 = K_1$

$k_2 + c_2 = k_2$

$k_3 + c_3 = k_3$

$k_4 + c_4\, cos\theta(x) + c_4 = k_4\, cos\theta(x)$

Therefore,

$T(x, x, t) =$
$c_2\dot{x}^2 + c_3\dot{x} + c_4\, cos\theta(x) + c_4 + K_5\, sin\theta(x)$
32

Transforming equation 32 into its original coordinate system, also note that the push rim is mounted on the spoke of the rear wheel. Then

$$F = F_{pr} - \sum_{i=1}^{N} f_1$$

33

$$= F_{pr} - \sum_{i=1}^{N} k_1 d_1$$

Since all the forces tangential to the push rim does no go into propulsion, then

$F_{net} = F - \sum_{i=1}^{N} R$
34

Equation 34 represents the force available to accelerate a given wheelchair when effort is applied to the rear wheel knowing fully that (R) represents the total resistances before and during propulsion.

Result and Discussions

From our findings, a total force of 1354 N and 1425 N for average female and male adult's paraplegic are required to access points of service provisions up an inclined plane at an angle of 30^0. It is quite clear that the forces required to propel a wheelchair by a paraplegic up an inclined plane has been developed. From the expression, it requires a large magnitude of force to overcome resistances posed by frictions arising from the angle of inclination, the height of the plane, the distance, and others such as air resistance and that of the mobility aid used. The force required to overcome this task respectively, is capable of creating epidemiological conditions in Paraplegics since the upper thoracic cavity was not designed and equipped for such task. This condition, promotes some health challenges to these set of persons in addition to their inherent problems of lower limb deformity coupled with their social, emotional and physiological status. To avoid these ugly challenges partly responsible for the low life style and self-esteem suffered by Nigerian adult paraplegics, it becomes imperative that government at all levels as a matter of urgency adhere to the principle of inclusive design policies in all public projects slated for execution in Nigeria. For an average Nigerian adult paraplegics, the magnitude of the force required to overcome the resistance posed by an inclined plane to access points of service provisions remained so large and daunting that most times they are discouraged in involving themselves in certain productive ventures. This therefore calls for urgent attention on part of government, churches, philanthropist and other well-meaning individuals.

Conclusion

From the analysis and the theoretical formulation, it is clear that the force required by an average Nigerian adult paraplegic is so large that when practiced repeatedly, it will create an epidemiological condition that may be detrimental to their health status. This explains why they are muscularly built around their thoracic cavities. This again is dangerous for these class of persons added to the societal traumas they face on a daily basis.

It is therefore recommended that a special paraplegic centricity mobility aid be made available to these class of persons. Evidently, it is our view that Government, Churches, Philanthropists and Non-governmental organizations should use this document to affect the lives of these groups of persons.

If this is properly done, they will be able to access their points of service delivery, be productive to themselves and the nation, have increased self-esteem and above all contribute meaningfully to the growth of the gross domestic product (GDP) of the Federal Republic of Nigeria.

References

Ashiedu, F. and Igboanugo, A. C. (2010) A Factorial Study of Accessibility requirements of paraplegics' mobility in a built up environment in: Laryea, S, Leringer, R. and Hughes, W. (Eds) procs West Africa Built environment research (WABER) Conference, 27-28 july 2010, Accra, Ghana, 35-47.

Arva, J, Paleg, G, Lange M (2009) RESNA Position on the application of wheelchair standing device. Assistive Technology Vol. 21, Pp (161-168).

Ayodeji, S. P., Adejuyigbe, S. B., and Abiola, A. K., (2008) "Anthropometric Survey of Nigerian Paraplegics". African Journal of Science and Technology Ghana. Vol 28(3) Pp (70-81).

Ayodeji, S. P. and Adejuyigbe, S. B. (2008) Development of CAD Software for Wheelchair Design. African Journal of Science and Technology (Ghana) vol. 28(3) Pp (82-93)

Ebrahimi, Alireza Kazemi and Azin Ebrahimi (2016) Wheelchair Design and its Influence on Physical Activity and Quantity of Life Among Individuals: Irenian Rehabilitation Journal vol. 14 No 2, Pg (85-92)

Ravenek, K.E, Ravenek, M.L, Hitzig, S.L and Wolfe D.L (2012) Accessing quality of life in relation to physical activity participation in persons with spinal cord injury: a review: Disability and health journal. Vol 5, No 4 Pp (213-223). DoI:10.10/6/J.dhjo.2012.05.005.

Kawanishi, C.Y, and Greguol, M (2013) Physical activity, Quality of life and functional autonomy of adults with spinal cord injuries. Adapted physical activity quarterly vol.30 No 4 Pp (317-337) doi:10.1123/apaq.30.4.317.

Van der Wounde, L.H, De Groot, S, and Janseen, T.W (2006) Manual Wheelchairs: Research and Innovations in Rehabilitations, Sports, Daily life and Health; Medical engineering and Physics Vol 28, No 9, Pp (905-915).

Gautam Dawar, Aneeshi Kejawal and Devender Kumar (2019) Design of a modular wheelchair with posture transformation capabilities from sittiong to standing. Disability and Rehabilitation: Assistive Technology. Doi:10.1080/17483107.2019.1604830. https//doi.10.1080/17483107.2019.1604830.

Goher K.M (2013) Modelling and Simulation of a Reconfigurable Wheelchair with sit-to-stand facility for a disabled child: 18th international conference on methods and models in Automation and robotics August (26-29) Miedzyzdroje, Poland, IEEE 2013.

Oden, I. and Knutsson E. (1981) Evaluation of the effects muscle stretch and weight load in patients with spastic paraplegics. Scand J Rehabil Med. Vol 13, Pp ()117-121).

Lizama-Tronscoso M.A, Serranco-Acevedo, D and Martell-Solares D. (2003). Inventors. University of Puerto Rico, assignee. Mechanically assisted standing wheelchair. United States patient US65330482.2003 March 18.

Kamnik, R and Bajd T. (2004). Standing up Robot: an assistive rehabilitative device for training and assessment. J.Med.Eng.Technol. Vol.28 Pp (74-80).