COBEM-2017-1878
AN ANALYTICAL APPROACH FOR THE PREDICTION OF THE PROFILE OF FORCES OF A MANUAL WHEELCHAIR PROPULSION

Denize Vilela Novais
Márcio Peres de Souza
Federal University of Uberlândia, School of Mechanical Engineering,
Habilitation/Rehabilitation Center in Paralympic Sports (NH/Resp),Uberlândia, MG, Brazil
denizemecanica@yahoo.com.br
marcioperes@ufu@ufu.br

Cleudmar Amaral de Araújo
Federal University of Uberlândia, School of Mechanical Engineering,
Habilitation/Rehabilitation Center in Paralympic Sports (NH/Resp),Uberlândia, MG, Brazil
cleudmar.araujo@ufu.br

Marcília Valéria Guimarães
Federal University of Uberlândia, School of Mechanical Engineering,
Habilitation/Rehabilitation Center in Paralympic Sports (NH/Resp),Uberlândia, MG, Brazil
marciliavguimaraes@gmail.com

Diego Augusto Costa Alves
Federal University of Uberlândia, School of Mechanical Engineering,
Habilitation/Rehabilitation Center in Paralympic Sports (NH/Resp),Uberlândia, MG, Brazil
diegoaugusto@ufu.br

Abstract. Studies have shown that propulsion forces affect directly manual wheelchair users (MWUs), whether they are athletes or not, who depend on a wheelchair for their mobility. Paralympic athletes, in particular, use them for sports, ambulation and also for training. These repetitive efforts of the upper limbs can lead to injuries and shoulder pain, resulting in decreased athletic performance and quality of life. The aim of this study was to predict the profile of propulsion forces in a manual wheelchair (MWC) by means of a quasi-static analytical model. The model of the effective force using Matlab® software permitted an evaluation of the conditions that lead to higher levels of force and a determination of the most favorable conditions to ensure lower force levels.

1. INTRODUCTION

According to the latest demographic census in Brazil, more than 45 million have some type of disability, corresponding to 23.9% of the population, as reported by the Brazilian Institute of Geography and Statistics (IBGE, 2010). Unfortunately, this census does not specifically show about physical disabilities such as the exact number of wheelchair users. With respect to the sports field, the researchers have given focus to wheelchair sports due to diversity of individual physiological impairments and the integrated unit formed by the athlete and their equipment. An individualized approach is needed in consequence of this diversity of physical disabilities to support wheelchair athletes and thus improve sports performance through of the technology, science and medicine of the sports (Griggs, *et al.*, 2016).

The repetitive nature of wheelchair propulsion has been associated with the high incidence of injury among manual wheelchair users. For almost twenty years, the biomechanics of propulsion in a wheelchair has been studied by scientists and engineers in order to prevent musculoskeletal injuries and underwent a kinematic assessment of propulsion in a wheelchair (Shimada, *et al.*,1998). In 2008, Collinger and colleagues conducted a study of shoulder biomechanics (kinetic and kinematic analysis) during the push phase in a wheelchair in three different laboratories with 61 paraplegic volunteers that use a wheelchair for mobility. In addition, they evaluated pain during the movement at

determined speeds. The authors realized that interventions aimed at reducing the force required to boost a CR should be implemented, such as maintaining body weight, to reduce the prevalence of shoulder pain and injury among these users.

Van der Woude and researchers (2001) mentioned that, despite the advancement of technology, the propulsion technique was still not well understood and that biomechanical research had been oriented to the musculoskeletal problems of long-term use of wheelchairs and sports. The increase of studies of the propulsion in manual wheelchair is due, in addition to the increase of the performance, the knowledge of the high loads imposed in the upper limbs that lead to injuries in the shoulder, forearm and in the wrist.

The wheelchair propulsion is comprised of two phases: the push (or propulsion) and a recovery phase. In the push phase the hands are in contact with the handrims and the force is applied by the athlete to it. Once the athletes hold the handrims and automatically follows the circular movement of it, the movement of the hands and arms can be characterized as a guided movement and therefore the forces that are applied by the hands do not directly influence the trajectory of the hands. In consequence it is possible to apply force that is not tangential to the handrims and any force that has a tangential component will contribute to the propulsion, therefore the authors conclude that the propulsion force may be, but not necessarily tangentially applied to the hoops (van der Woude, *et al.*, 2001).

In the 2016 Paralympic Summer Games in Rio de Janeiro, more than 4300 athletes with disabilities in 22 sports modalities participated. In numbers, among sports that use wheelchairs, for example, the wheelchair basketball with 263 competitors, wheelchair fencing with 89 competitors, wheelchair rugby with 96 competitors and wheelchair tennis with 100 competitors (IPC, 2016a, IPC, 2016b), almost 600 competitors only in these modalities. These numbers show the importance of studying the propulsion forces applied in manual wheelchairs in order to minimize the damage caused by repetitive movements whether in high performance athletes or for those people who use it in their daily living activities. The objective of this work is to predict the profile of propulsion forces in the rings of a MWC by developing an analytical model based on resistive forces and some aspects of the biomechanical movement to find the optimum conditions of the movement of less effort for the propulsion.

2. PROPOSED ANALYTIC MODEL

Figure 1 shows the free body diagram of applied forces in one of the rear wheels of a manual wheelchair upon an inclined plane at the imminence of the propulsive movement. The angle θ is the inclination of this plane in respect to the ground; F is the propulsion force applied to the handrims of radius r and transmitted to the wheels of radius R. N corresponds to the normal force that is generated by the contact of the wheels with the ground, μN is the frictional force opposite to the movement (μ = friction coefficient between ground and the tires) and n is the rotation of the set. For this work, P represents the weight force of system and P_c is the portion of the total weight applied to the rear wheels. According to Hofstad and Patterson (1994) P_c correspond to 60% of the total weight P, thus it was considered that the total weight distributed in each rear wheel as $0,3P$.
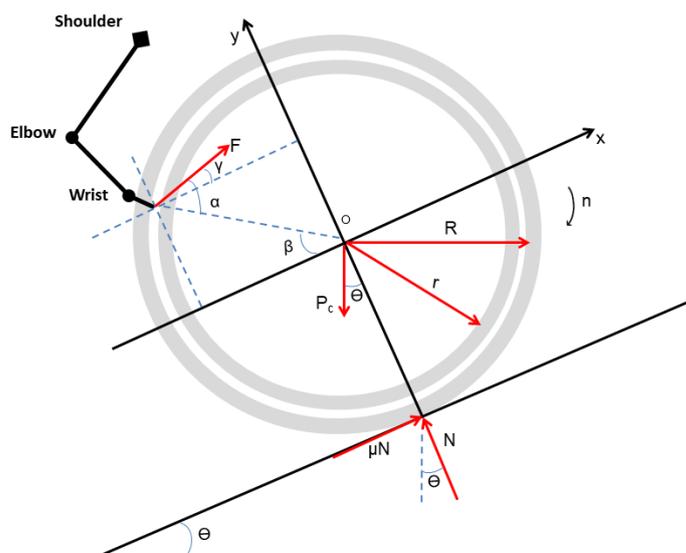

Figure 1. Free body diagram in the rear wheel of a MWC

The angle (β), as shown in Figure 1, is the angle between the x axis and the handrim radius in the position of application of the propulsion force and represents the position where the force will be applied on the handrims, while the angle (α) indicates the direction of application of the propulsion force relative to the handrim radius. These angles are decisive for generating effective torque and are limited by the joints range of motion. The minimum effort condition for wheelchair movement would be the applied force tangent to the handrim, but it is not always possible that this force does not contain a radial component, especially for untrained MWUs.

It is considered a condition of static equilibrium at the beginning of the movement. According to that, Newton's First Law can be applied to determine the propulsion force (Hibbeler, 2000) so the forces and moments acting upon a system in equilibrium is zero. According to the xy coordinate system, shown in Fig. 1, the resultant force in y direction:

$$\sum Fy = 0 \tag{2.1}$$

$$N - P_c \cos\theta + Fsen(\alpha - \beta) = 0 \tag{2.2}$$

$$N = P_c \cos\theta - Fsen(\alpha - \beta) \tag{2.3}$$

Summing moments about the O point, gives:

$$\sum M_0 = 0 \tag{2.4}$$

$$Frsen\alpha - \mu NR = 0 \tag{2.5}$$

Isolating F, we obtain:

$$F = \frac{\mu R}{rsen\alpha} N \tag{2.6}$$

Substituting the Eq. (2.3) in the Eq. (2.6):

$$F = \frac{\mu R P_c \cos\theta}{rsen\alpha + \mu Rsen(\alpha - \beta)} \tag{2.7}$$

Taking into account that P_c equals $0,3P$ in each rear wheel and suppose that wheelchair propulsion is on the ground level, therefore $\theta = 0°$, and the Eq. (2.7) can be rewritten as:

$$F = \frac{0,3\mu RP}{rsen\alpha + \mu Rsen(\alpha - \beta)} \tag{2.8}$$

Considering a positive propulsion, according to the Eq. (2.8), so that F to be valid the following conditions must be obeyed from Eq. (2.9) and Eq.(2.10).

$$rsen\alpha + \mu Rsen(\alpha - \beta) > 0 \tag{2.9}$$

where,

$$\mu R sen(\alpha - \beta) > -r sen\alpha \tag{2.10}$$

According to Becker (2000) the effective force F_{eff} corresponds to a propulsion force subtracted the rolling resistance due to the friction, so F is smaller than effective force, as shown in Eq. (2.11):

$$F_{eff} = F\frac{R}{r} - F_a \tag{2.11}$$

where F_a is the rolling force, F is the propulsion force, F_{eff} is the effective propulsion force and (R/r) is ratio between of the wheel R and handrim radius r . Then, the Eq. (2.11) can be rewritten by replacing in the Eq. (2.8),

$$F_{eff} = \left(\frac{0,3\mu RP}{r sen\alpha + \mu R sen(\alpha - \beta)}\right)\frac{R}{r} - F_a \tag{2.12}$$

In the imminence of movement, for $\theta = 0°$, without effectively apply a propulsion force on the wheelchair it can be assumed that the normal reaction depends only on the portion of the weight force P_c , therefore:

$$N = P_c \tag{2.13}$$

Replacing, the normal force from Eq. (2.13) in the rolling force, called F_a , so

$$F_a = \mu N = \mu(0,3P) \tag{2.14}$$

Thus the effective force from Eq.(2.12) can be rewritten as,

$$F_{eff} = \left(\frac{0,3\mu RP}{r sen\alpha + \mu R sen(\alpha - \beta)}\right)\frac{R}{r} - 0,3\mu P \tag{2.15}$$

3. PROPULSION EFFICIENCY SIMULATION IN A MANUAL WHEELCHAIR

This simulation was performed through the numerical solution of the Eq. (2.15) using a Matlab® code and for that was used different combination of (α) and (β) defined in accord to the reference system used. The results show a profile of propulsion effective forces required in each kinematic conditions simulated. The variables used in this analysis are presented in Table 1.

Table 1. Variables used in the simulation of effective force.

Variables	Values
θ	0°
μ [1]	0,08
P	70 kg
P_c	$0,3P$ =21 kg
R	302,5 mm
r	270,0 mm
α	70° - 90°
β	60° - 120°

[1] Source: BECKER (2000)

4. RESULTS AND DISCUSSION

Figure 2 illustrates the profile of propulsion effective forces simulated by Eq. (2.15) as a function of the angles α and β .
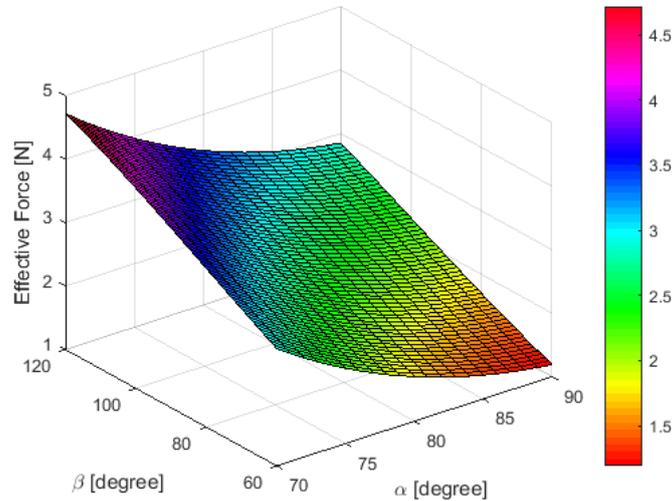

Figure 2. Profile of propulsion forces on the handrim of MWC

Table 2 shows effective force values for some analysis condition.

Table 2. Effective force values.

Effective Force (N)							
Beta Alpha	60°	70°	80°	90°	100°	110°	120°
70°	2,849	3,169	3,500	3,832	4,153	4,452	4,718
75°	2,187	2,482	2,792	3,106	3,415	3,710	3,978
80°	1,703	1,977	2,269	2,570	2,871	3,163	3,438
85°	1,375	1,633	1,910	2,201	2,496	2,787	3,063
90°	1,192	1,435	1,701	1,984	2,276	2,568	2,850

It can be noted in the Fig. 2 that exists particular conditions where the level of forces applied to the handrims are maximum to promote the wheelchair propulsion, for example in the Tab. 2, in a position ahead of the wheel axis $\alpha = 70°$ and $\beta = 120°$ ($F_{eff} = 4,718$ N) compared to the force in the axis position $\alpha = 90°$ and $\beta = 60°$ ($F_{eff} = 1,192$ N) which represents a 25.26% lower force than the first condition. These points correspond to certain biomechanical conditions where propulsion must be avoided. The analyzes performed in this study did not take into consideration the continuity of the movement, air resistance and the biomechanics limitations, in the other words, the joints range of motion related (shoulders, elbows and wrists). According to Vanlandewijck, Theisen and Daly (2001) the most important problem to be addressed is the force application strategy of the wheelchair users.

5. CONCLUSIONS

This work showed that the proposed model for effective propulsion force is suitable for biomechanical analysis of MWC propulsion forces. The results indicate that the best wheelchair propulsion condition corresponds to $\alpha = 90°$ and $\beta = 60°$, in this point it is possible begin the wheelchair movement with the minimum effective force (F_{eff} = 1,192N) in the range analyzed. Referring to Fig. (1), it is possible to understand this kinematic condition implies in carrying out a propulsion movement by beginning the movement at 30° away from the y direction with a tangent force to the propulsion handrim.

6. ACKNOWLEDGEMENTS

7. REFERENCES

Becker,M. 2000. "*Aplicação de Tecnologias Assistivas e Técnicas de Controle em Cadeiras de Rodas Inteligentes*". Tese de Doutorado, Universidade Estadual de Campinas, Faculdade de Engenharia Mecânica, Campinas.

Collinger, J.L., Boninger, M.L., Koontz, A.M., Price, R., Sisto,S.A., Tolerico, M.L. and Cooper, R.A., 2008. "Shoulder biomechanics during the push phase of wheelchair propulsion: a multisite study of persons with paraplegia". *Archives of Physical Medicine Rehabilitation*. n.89, p.667-676.

Griggs, K., Goosey-Tolfrey, V. and Paulson, T., 2016. "Supporting paralympic wheelchair sport performance through technological, physiological and environmental considerations". *Annals of Human Biology*. Vol.44, n.4,p.295-296.

Hibbeler, R. C., 2000. *Resistência dos Materiais*. Rio de Janeiro: LTC,701p.

Hofstad, M., Patterson, P.E.,1994. "Modelling the propulsion characteristics of a standard wheelchair". *Journal of Rehabilitation Research and Development*. Vol. 31, n.2, p.129-137.

IBGE, 2010. "Censo Demográfico 2010 – Características gerais da população, religião e pessoas com deficiência". 18 Sept. 2017 <https://biblioteca.ibge.gov.br/visualizacao/periodicos/94/cd_2010_religiao_deficiencia.pdf>.

International Paralympic Committee (IPC), 2016a. "Rio 2016 Paralympic Games" 18 Sep. 2017 <https://www.paralympic.org/rio-2016>.

International Paralympic Committee (IPC), 2016b. "IPC Historical Results Archive – Rio 2016 Paralympic Games". 18 Sept. 2017 <https://www.paralympic.org/results/historical?sport=3&ct=PG&ordered=1#general>.

Shimada, S.D., Robertson, R.N., Bonninger, M.L., Cooper, R. A., 1998. "Kinematic characterization of wheelchair propulsion". *Journal of Rehabilitation Research and Development*. n.35, p.210-218.

Van der Woude, L. H. V., Veeger, H. E. J., Dallmeijer, A. J., Janssen, T. W. J., & Rozendaal, L. A., 2001. "Biomechanics and physiology in active manual wheelchair propulsion". *Medical Engineering and Physics*. Vol.23, n.10, p.713-733.

Vanlandewijck, Y., Theisen, D., and Daly, D.,2001. "Wheelchair propulsion biomechanics". *Sports Medicine*. Vol.31, n.5, p.339-367.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.