Effect of Added Mass Location on Manual Wheelchair Propulsion Forces

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Abstract. This study investigated the influence of mass distribution on the handrim forces during manual propulsion in four different mobility tasks: straightforward motion at self-selected speed; straightforward sprint; zero radius turn; and circular trajectory. A foldable-frame wheelchair was instrumented with a SmartWheel system placed on the right side. Three different positions of an additional mass of 7.8 kg were investigated: in the center of the rear wheels' axle; on the spokes of each of the two rear wheels; under the footrest. When mass is added in a centered position, there is little effect on the level of forces required to propel the chair, while when the additional mass is positioned distant to the wheelchair center, namely rear wheels' spokes and feet support, the effect on propulsion forces is increased. Optimizing wheelchair mobility efficiency requires an understanding on the effects of changes in equipment configuration on propulsion kinetics.

Keywords: Wheelchairs · Propulsion kinetics · Mass distribution · Mobility · Wheelchair configuration.

1 Introduction

Manual wheelchairs are probably the most common means of mobility used by people with physical disabilities allowing the ability to walk independently and safely. The wheelchairs provide mobility and independence for the users, however the locomotion method used in manual wheelchairs is still mechanically inefficient and physiologically demanding [1]. Studies show that shoulder pain affects up to 73% of wheelchair users, and of these, around 84% tend to reduce participation in sports and leisure activities, and have difficulty performing other daily tasks [2].

Ergonomic approaches have been proposed to reduce the biomechanical loads during manual propulsion. Alternative systems such as lever propulsion [3], geared wheels [4] showed potential benefits in reducing biomechanical demands but requires the user to adapt to a new propulsion mode. Pushrim activated power assisted wheelchairs also showed promising results in terms of reducing loads [5]. Additionally,

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innovative mechanism of providing complimentary torque by a single motor to both of the rear wheels has been proposed [6-8]. However, still the conventional manual wheelchair design remains the most globally used means of seated mobility. Therefore, investigating wheelchair design factors that are related to optimal mobility performance is necessary to improve efficiency and reduce the biomechanical risk related to prolonged use of manual wheelchairs.

Wheelchair professionals must be aware that there are several important aspects in the design and configuration of manual wheelchairs that may influence propulsion loads, stability and ultimately, mobility efficiency. The position of rear wheels' axle relative to the seat/user, wheels and tires types, frame design and accessories, casters' size and material are among the most relevant factors [9]. Mechanically, the configuration of these aspects in the wheelchair design determine the equipment mass, size and mass distribution. Mass distribution has been shown to influence resistive losses during manual wheelchair propulsion [10].

Altering weight distribution in daily use wheelchairs may result in changes in wheelchair configuration, use of accessories and the carriage of belongings. The influence of such changes in the mechanics of wheelchair design may affect required force to propel the chair in daily mobility. In order to explore the effects of wheelchair design on propulsion forces, this study was set out to investigate the influence of added mass location on handrim forces of the rear wheels.

2 Materials and Methods

2.1 Participants

A convenience sample of five male subjects without physical disabilities (average age of 31.8 ± 8.4 years, average height of 1.73 ± 0.06 meters, and average weight of 77.5 ± 6.4 kg) was recruited at the São Paulo State University (UNESP, Bauru, Brazil). Participants met the following inclusion criteria: (a) minimum age of 18 years old; (b) had no upper limb pain, injuries or disorders that could influence the manual wheelchair propulsion. Prior to data collection, volunteers were informed about the study and signed an informed consent form that had been approved by Ethics Committee of the FAAC/UNESP (Process 800.500).

2.2 Equipment and procedures

A manual rigid frame wheelchair (Starlite, ORTOBRAS, Brazil) (total mass 13 kg) and the instrumented wheel SmartWheel system (ThreeRivers CO, United States) were used. The SmartWheel system consists of a sensing system which enables the analysis of the forces and movements due to the manual forces applied on the rear wheels of a wheelchair. The system weights 4.3kg, and since it was connected only to the right side of the chair (participants' dominant side), a compensation weight of 2.6 kg was added on the opposite wheel (1.7 kg) in order to avoid the asymmetry.

In order to analyze the impact of changes of the center of mass in the system wheelchair/user were used six similar weight plates (1.3 kg each) totaling 7.8 kg. In this sense the test had as a variable factor the center of mass of the total wheelchair-weight, represented by the weight distribution of the plates in three different situations. The wheelchair was configured with three weight plates distributed radially on each rear wheel (3.9 kg), as shown in Fig. 1(a). This configuration simulates a possible variation of weight in the wheels according to the different models and brands of rear wheels as well as tires and handrim. In the second configuration, all the additional weight (7.8 kg) was placed on the center of the rear axle of the chair (see Fig. 1(b)), in order to simulate different models and materials of the wheelchair frame. The third configuration comprised fixing the six weight plates on the footrest. This mass distribution simulated changes in the mass concentration in the anterior part of the chair as a result of different parts e.g., different caster models and/or different angles of the user's legs (see Fig. 1(c)).

Fig. 1. Added mass on (a) the rear wheels' spokes; (b) on the center of rear wheels' axle; (c) under the foot support.

Participants familiarized themselves with the field test and the wheelchair before the data collection. The orders of the conditions were randomized to eliminate possible effects of learning or fatigue. The test comprised a sequence of four maneuvers performed in a flat surface: straightforward propulsion (five pushes) at self-selected speed; straightforward propulsion (five pushes) at maximum speed (sprint); 360 degrees anti-clockwise rotation around the participants' own axis (zero radius turn) at a comfortable speed; one-meter radius anti-clockwise turn without a specific number of touches. Each of these maneuvers were repeated three times for each chair configuration. As the SmartWheel was placed on the right side, the turning maneuvers were performed in anti-clockwise direction so that the concentration of the forces occurred in the instrumented wheel.

All the trials of each participant were conducted during the same day, without the need for a rest between the maneuvers. In none of the collections were there complaints of the subjects due to the efforts employed in carrying out the maneuvers. The kinetic variables addressed in this study are: Peak total force ((Peak Ftot [N]), Peak moment along the Z-axis (Peak Mz [N*m]), peak tangential force (Peak Ft [N]) Average total force (Ave Ftot [N]), average tangential force, peak/average force ratio.

3 Results and Discussion

Propulsion forces are important variables that directly affect the performance of manual wheelchair mobility. From the total force applied to the handrim, the component that most contribute to the wheelchair movement is the tangential force, although the axial and radial components are necessary to stabilize the hand-handrim coupling with enough friction for the push force actuation. From the perspective of handrim kinetics, manual propulsion efficiency refers to the ability of pushing the wheels with a greater tangential component. The analysis of the propulsion forces applied to the handrims during straight line displacement showed that the force in the first push was approximately 30% larger than the four consecutive pushes, which is due to the greater effort needed to put the chair in motion compared to the effort required to maintain the movement (see Fig. 3). Additionally, Fig. 3 shows that the handrim forces during the braking maneuver exhibited a similar pattern to the forward pushes, but in the opposite direction. From a clinical perspective, it is important to provide the user with lightweight wheelchairs and training of the correct propulsion technique for the first pushes, as high forces are factors that contribute with exposure to risk of injuries [11].

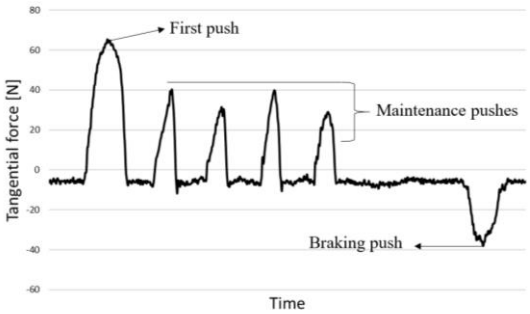

Fig 2. Tangential force during the five consecutive pushes and a sixth action of breaking in straightforward propulsion.

Conversely, the addition of mass in the foot support led to an increase of 12.1% in the total peak force (Peak Ftot) in straightforward sprint, 2.2% in the straight line propulsion at self-selected speed, 14.3% for the zero-radius turn maneuver and 12.6% for the one-meter radius circle maneuver when compared to the configuration with the additional mass on the center of the rear wheels' axle. The analysis of the tangential component of the handrim force (Ft) showed an increase of 27.2% for the zero-radius turn and 17.2% for the 1 m-radius circle compared to the configuration with the additional mass on the center of the rear wheels' axle, demonstrating that the effect of the mass addition on the propulsion biomechanics depended on the location in the wheelchair geometry.

Table 1 demonstrates that, both peak and mean total and mean forces were lower when the wheelchair mobility tasks were performed with the wheelchair with the added mass located on the center of the rear wheels' axle in comparison to the added mass on the rear wheels' spokes and foot support. Furthermore, for most of the tasks, the condition with added mass under the foot support was associated with greater forces, possibly due to the weight concentration on the casters, which results in increased rolling resistance that, ultimately, demand stronger pushes from the user to maintain the expected velocity. Smaller wheel sizes are associated with increased rolling resistance [9]. Therefore, optimizing wheelchair configuration in a way that the wheelchair-user system's center of mass is positioned closer to the rear wheels can benefit propulsion efficiency by reducing rolling resistance.

Table 1. Average propulsive forces of the five participants, in the three conditions of added mass location and four different trajectories.

Configuration	Movement	Peak Ftot [N]	Peak Mz [N*m]	Peak Ft [N]	Ave Ftot [N]	Ave Ft [N]	Peak/Average Force Ratio
Weight on the rear wheels' spokes	Forward Self-selected speed	56.48	15.57	60.56	41.07	41.08	1.48
	Forward sprint	118.44	32.97	128.19	74.83	75.99	1.73
	Zero radius turn	44.17	10.95	42.57	33.49	29.62	1.42
	Círculo Raio 1m	58.49	14.93	58.04	43.48	39.34	1.48
Weight on the rear wheel axle	Forward Self-selected speed	56.89	14.76	57.38	41.82	38.95	1.48
	Forward sprint	104.45	31.47	122.37	69.67	74.00	1.68
	Zero radius turn	40.58	9.56	37.18	31.88	26.58	1.37
	Círculo Raio 1m	57.63	14.57	56.65	43.15	38.44	1.47
Weight under the footrest	Forward Self-selected speed	58.17	15.63	60.79	42.19	40.98	1.49
	Forward sprint	118.81	33.63	130.75	77.14	80.86	1.64
	Zero radius turn	47.37	13.13	51.07	34.48	31.76	1.64
	Círculo Raio 1m	65.95	17.59	68.41	46.61	45.32	1.50

It is interesting to note the differences in the forces according to the mobility task. Considering the average total force, the less demanding situation was the zero-radius turn. When comparing straight line propulsion at self-selected speed and sprint, we found increases in the average total force of 66.6% with the added mass on the center of the rear wheels' axle, 75.7% with the mass under the foot support and 82.2% with the mass on the rear wheel spokes. A previous study demonstrated how trajectory influences kinetic energy of a wheelchair in motion [12].

Encouraging active wheelchair use can contribute to independence and social participation. A previous study demonstrated the benefits of practicing wheelchair sports for the users' quality of life [13]. In this context, a key factor is to provide wheelchairs with a design and configuration that allows optimal mobility performance.

This study has limitations that must be noted. The small sample size and the fact that participants had no previous experience with wheelchair usage limit the generalizability of the findings.

4 Conclusions

This study found that added mass location influences manual propulsion forces in different trajectories. Considering the same trajectory, lower handrim forces were found when the additional mass was positioned in a centered position on the rear wheels' axle, which is closer to the system center of mass. On the other hand, the condition that demanded greater forces was the one with the added mass under the foot support. As for the trajectory, forward sprint was associated with higher levels of force, followed by circular trajectory. The less demanding trajectory was the zero-radius turn. In the design, provision and adjustment of manual wheelchairs, one must consider the potential effects that changes in the mass and mass distribution as result of changes in wheelchair design, configuration and the use of accessories can have on the demand of propulsion forces. Optimizing wheelchair design to reduce handrim propulsion forces must be addressed in order to benefit mobility efficiency and minimize the biomechanical demand for the user.

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References

1. Kabra, C., Jaiswal, R., Arnold, G., Abboud, R., & Wang, W.: Analysis of hand pressures related to wheelchair rim sizes and upper-limb movement. International Journal of Industrial Ergonomics, 47, 45-52. (2015)
2. Rossignoli, I., Fernández-Cuevas, I., Benito, P. J., & Herrero, A. J.: Relationship between shoulder pain and skin temperature measured by infrared thermography in a wheelchair propulsion test. Infrared Physics & Technology, 76, 251-258. (2016)
3. Lui, J., MacGillivray, M. K., Sheel, A. W., Jeyasurya, J., Sadeghi, M., Sawatzky, B. J.: Mechanical efficiency of two commercial lever-propulsion mechanisms for manual wheelchair locomotion. Journal of Rehabilitation Research & Development 50(10), 1363-1372 (2013)
4. Howarth, S.J., Polgar, J.M., Dickerson, C.R., Callaghan, J.P.: Trunk muscle activity during wheelchair ramp ascent and the influence of a geared wheel on the demands of postural control. Arch Phys Med Rehabil. 91(3), 436-42 (2010)
5. Lighthall-Haubert, L., Requejo, P.S., Mulroy, S.J., Newsam, C.J., Bontrager, E., Gronley, J.K., Perry, J.: Comparison of shoulder muscle electromyographic activity during standard manual wheelchair and push-rim activated power assisted wheelchair propulsion in persons with complete tetraplegia. Arch Phys Med Rehabil. 90(11):1904-15 (2009)
6. Medola, F.O., Purquerio, B.M., Elui, V.M., Fortulan, C.A.: Conceptual project of a servo-controlled power-assisted wheelchair. In: IEEE RAS & EMBS International Conference on Biomedical Robotics and Biomechatronics, pp. 450–454. IEEE (2014)
7. Lahr, G.J.G., Medola, F.O., Sandnes, F.E., Elui, V.M.C., Fortulan, C.A.: Servomotor assistance in the improvement of manual wheelchair mobility. Stud. Health Technol. Inf. 242, 786–792 (2017)
8. Medola, F.O., Bertolaccini, G.S., Silva, S.R.M., Lahr, G.J.G., Elui, V.M.C., Fortulan, C.A.: "Biomechanical and perceptual evaluation of the use of a servo-controlled power-assistance system in manual wheelchair mobility", International Symposium on Medical Robotics (ISMR), 2018.
9. Medola, F.O., Elui, V.M.C., Santana, C.S., Fortulan, C.A.: Aspects of Manual Wheelchair Configuration Affecting Mobility: A Review. J Phys Ther Sci. 26(2): 313–318 (2014)
10. Sprigle, S., Huang, M.: Impact of Mass and Weight Distribution on Manual Wheelchair Propulsion Torque. Assist Technol. 27(4):226-35 (2015)
11. Morrow, M. M., Hurd, W. J., Kaufman, K. R., & An, K. N.: Shoulder demands in manual wheelchair users across a spectrum of activities. J Electromyogr Kinesiol, 20(1), 61-67 (2010)
12. Medola, F.O., Dao, P.V., Caspall, J.J., Sprigle, S.: Partitioning kinetic energy during free-wheeling wheelchair maneuvers. IEEE Trans Neural Syst Rehabil Eng. 22(2):326-33 (2014)
13. Medola, F.O., Busto, R.M., Marçal, A.M., Achour Junior, A., Dourado, A.C. Sports on quality of life of individuals with spinal cord injury: a case series. Rev Bras Med Esporte, 17(4), 254-256 (2011)