Exploring the Relationship of Rolling Resistance, Tire Type, and Surface in Wheelchair Rear Wheels

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INTRODUCTION

The World Health Organization estimates that 20 million people in the world are in need of wheelchairs [1]. Most of these people reside in low resource areas where access to efficient wheelchairs is difficult. Certain non-profit organizations raise funds, design, and build wheelchairs for such low resource environments. These wheelchairs are typically funded by charitable donations, so it's important to minimize cost (typically below $300). For these generally remote areas, organizations must balance wheelchair quality, rough terrain capabilities, low maintenance, and cost. Access to rolling resistance data will allow manufacturers to include this as part of their wheelchair design process, allowing for cost effective and efficient solutions to be incorporated.

To determine rolling resistance properties of a certain wheel, the force that is needed to keep the wheel rolling at a constant velocity is measured. This is the rolling resistance force, F_{RR} shown in Equation 1. This classical equation states that the rolling resistance force, F_{RR}, equals the coefficient of rolling resistance, μ_{RR}, multiplied by W, the weight on the wheel.

$$F_{RR} = \mu_{RR} * W \qquad (1)$$

Therefore, the rolling resistance coefficient, μ_{RR}, can be calculated by dividing the rolling resistance force by the weight [2]. A wheel that has a smaller μ_{RR} will need less force to propel than another wheel that has a bigger μ_{RR} carrying the same weight. Less force to propel means less exertion for the user.

A survey of the literature reveals studies that determined impact on human effort due to wheelchair type and wheel camber using measurements of oxygen consumption, heart rate, and arm abduction angles [4,5]. Another study using wheelchair ramp rolling distance showed that rolling resistance increases of 4.2%, 11.8%, and 32% leads to a 3%, 12%, and 25% increase in user energy expenditure, respectively [3]. Rolling resistance has a significant impact on all users, however, those that travel long distances outdoors with softer and rougher surfaces especially need a wheelchair with a low rolling resistance. Wheels that roll easier allow the user to reach their destination without expending large amounts of energy.

Other studies evaluated ease of rolling an entire wheelchair, which is impacted by the rolling characteristics of the front casters, the center of gravity of the loaded wheelchair, and, in cases with humans, the efficiency and fit of the user. One study tested the rolling resistance of different types of rear wheels by using a cart on a treadmill [6]. The technique of measuring rolling resistance of wheelchair wheels on a cart separately from the wheelchair provides a repeatable, quantified parameter that analyzes the wheel itself as opposed to the whole wheelchair. However, this technique is limited on surface selection to that of the treadmill.

Another article described a mathematical model that can be used to predict rolling resistance relative to factors such as floor material, wheel type, and tire pressure. [7]. However, that study focused only on the indoor surfaces of a smooth floor and carpet. This study seeks to consider common outdoor surfaces as well.

Rolling resistance data is also collected by using a coast-down test with a loaded wheelchair on a drum dynamometer [8, 9]. In these tests, the wheelchair rides on drums that are spun at a constant angular velocity, then disengaged. An angular velocity that decreases rapidly shows a high rolling resistance. Such studies have shown that airless tires generally have higher rolling resistance than pneumatic tires. However, these tests only measure rolling resistance on a smooth metallic surface. In addition, correction factors need to be applied because rolling resistance is different on a curved drum surface, as opposed to actual earth terrain [9].

METHODS

The testing system consists of a cart, tow control, instrumentation, and data analysis. The cart was constructed with an aluminum T-slot frame that is used to mount three wheelchair wheels with an applied weight that is equally distributed between the three wheels (Figure 1). For this study, 22-inch non-pneumatic tires used by Hope Haven International and 26-inch pneumatic tires used by Free Wheelchair Mission were used. The pneumatic tires were within 10% of their maximum air pressure during testing, which was 50 psi.

Figure 1. Loaded cart on smooth

The cart is towed by a string wrapped on a drum which is rotated by a three phase AC motor. The motor is controlled by a variable frequency drive (VFD) that allows the system to operate at a chosen velocity. The VFD ramps up to the test velocity of 0.25 m/s gradually to minimize overshooting the target velocity.

Force data was collected using a 25-lb S-beam load cell (Omega Engineering, Norwalk CT) which is attached to the front of the cart. The tow cable is then clipped to the load cell with a carabiner. A laser distance sensor was used to ensure that the cart was being pulled at a constant velocity. Outputs from both sensors were sent to a portable computer through a National Instruments 9219 USB DAQ having 24 bit A/D conversion. LabVIEW was used to create a data acquisition interface to collect and store data for post-processing. Force and velocity measurements were then exported for data analysis.

Figure 2. Carpet testing surface

The cart was tested on several different surfaces. Tests were done at two weight levels equating to 33 lb and 66 lb on each wheel +/- 1 lb. Five trials are taken in each direction. The tests were done on polished tile (smooth floor), carpet, packed dirt, and concrete. Pictures of each testing surface can be seen in Figures 1-3. The carpet surface used is commercial carpet adhered to a melamine board, as seen in Figure 2. The smooth floor surface is the polished tile also seen in Figure 2. Packed dirt testing was done on a baseball field. The dirt that was tested was dry and packed. This surface can be seen in Figure 3. The smooth concrete used for testing can be seen in Figure 1.

Figure 3. Packed dirt testing

Matlab software (by Mathworks, Natick MA) was used for data selection and averaging. For each run, five seconds of data were selected towards the end of each trial. This data was averaged to find the mean force to pull the cart over the five seconds. Out of the five trials taken, the high and low means were removed. Therefore, three trials were used to calculate the average force to pull the cart for a particular wheel, surface, direction, and weight. The force average of the selected data was then exported to Microsoft Excel where the rolling resistance coefficient was calculated by dividing the average force by the weight. Histograms were created in Microsoft Excel comparing rolling resistance coefficients of the two wheels under various conditions. 95% confidence intervals were created in Minitab 18 (Minitab Inc, State College PA).

Validation of the apparatus was done using calibrated weights and coefficient of kinetic friction comparisons. Calibrated weights were hung from the load cell and the force was measured. Load cell readings were within 0.1% of the 2.440-lb weight and 0.3% of the 5.124-lb weight. The cart tow system was validated by pulling 9.6 and 24.8-lb weights across a plastic-coated wood panel known as melamine at a constant speed. The force readings were used to calculate the coefficient of kinetic friction. This value was then compared to kinetic friction values found by allowing gravity to slide the weights down the melamine panel tilted at an angle. It was found that the weights would slide at a constant velocity after an initial push at an angle of 14.6 degrees. This angle equates to a coefficient of kinetic friction of 0.26 for both weights. The values found from using the load cell and cart tow system on the same surface were 0.250 for the 9.6-lb weight and 0.284 for the 24.8-lb weight. This accuracy of 96 – 109% was deemed sufficient based on the precision of the methods used.

RESULTS

The results showed that the non-pneumatic wheel has a higher rolling resistance than the pneumatic wheel, which is consistent with previous studies (Figure 4). However, it is interesting that the non-pneumatic wheel performed almost as well as the pneumatic wheel on concrete below freezing temperature (25 ^{o}F). On dirt, non-pneumatic wheels showed rolling resistance higher than carpet, while the pneumatic tires were quite close to carpet values. The rolling resistance coefficient of the non-pneumatic wheel increased when weight was added to the cart on most surfaces. Meanwhile the rolling resistance coefficient of the pneumatic wheel does not show a clear relationship with weight. This provides some interesting information that should be considered when selecting a wheel for a person. Heavier individuals will have higher rolling resistance coefficients when using non-pneumatic wheels than lighter users will experience.

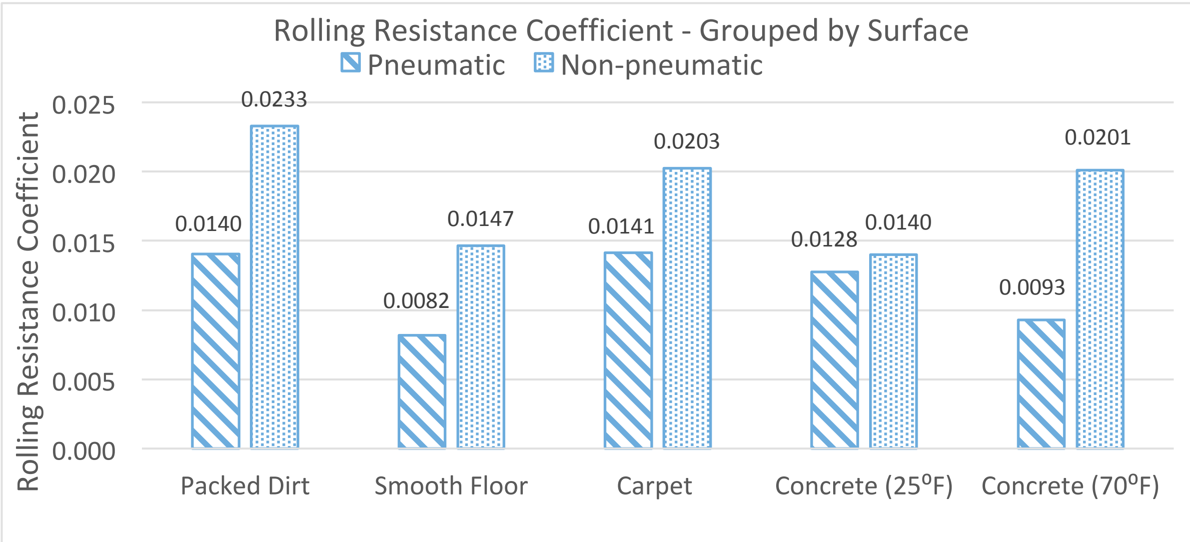

Figure 4. Average rolling resistance coefficients measured

Of the surfaces tested, dirt yielded the largest 95% confidence interval for the average rolling resistance, though it is still quite small. The rolling resistance coefficient interval is (0.0137,0.0143) for the pneumatic wheel and (0.0229,0.0235) for the non-pneumatic wheel. This gives an interval of 3.99% of the mean for the pneumatic wheel and an interval of 2.94% of the mean for the non-pneumatic wheel. These numbers are well within the satisfactory range for a 95% confidence interval.

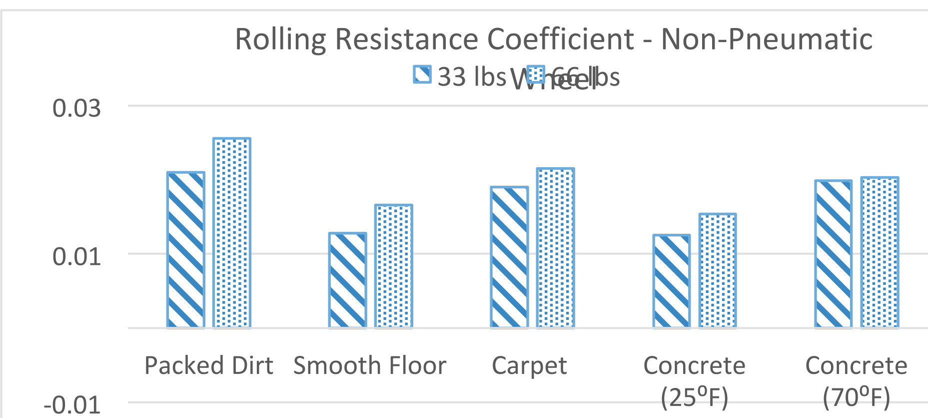

Figure 5. Rolling resistance coefficient averages for non-pneumatic wheels

DISCUSSION

The results show that pneumatic wheels behave differently than non-pneumatic wheels. It appeared that the temperature may play a role in rolling resistance for both wheels. The colder temperatures may increase the hardness of the polyurethane, allowing it to roll more efficiently over smooth surfaces. The cold weather also may have increased the resistance of the pneumatic wheels by lowering the tire pressure or making the rubber stiffer. Future studies should be done to examine the effect of temperature on rolling resistance in both pneumatic and non-pneumatic tires. It was also found that the rolling resistance coefficients of the non-pneumatic wheel increased with weight. This shows that it may be better to use the non-pneumatic wheels for children or those who have lower body mass.

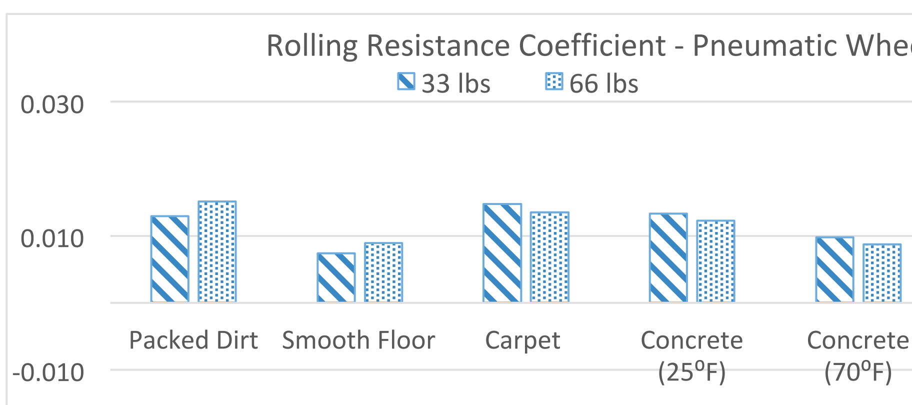

Figure 6. Rolling resistance coefficient averages for pneumatic wheels

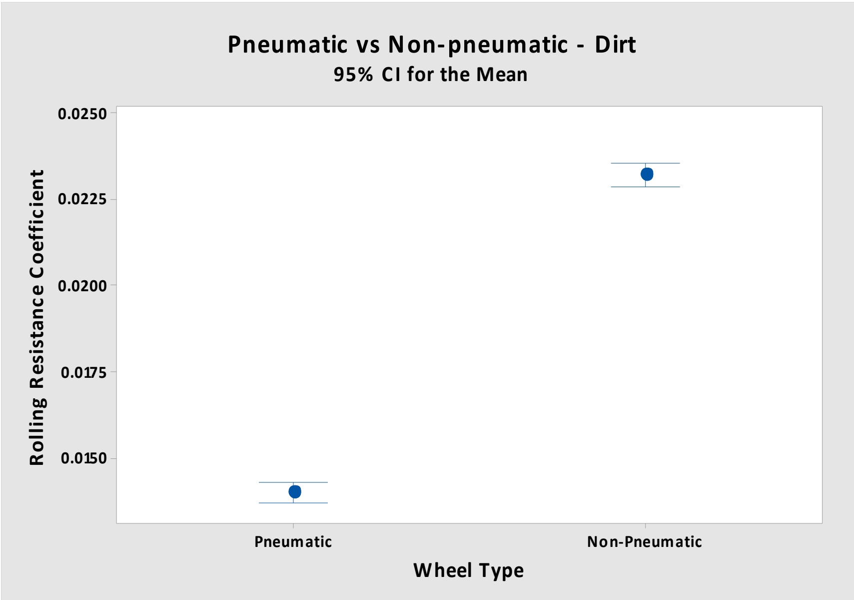

Figure 7. Confidence interval for data from dirt surface

The surface that the user will travel on most frequently should be taken into consideration when selecting a proper wheel. Those who travel greater distances may benefit from a pneumatic wheel while those traveling on smooth surfaces for short distances may benefit from the lower maintenance of the non-pneumatic wheel.

The rolling resistance tests in this study utilized only two types of wheelchair wheels. Also, the wheels were different diameter, which is known to affect rolling resistance. More studies are needed with other types of non-pneumatic and pneumatic tires in order to gain a better understanding of the differences between the tires. It would also be interesting to see how tread wear effects rolling resistance. Wheel bearings and frame rigidness may also play a part.

A user's access to maintenance, common travel surfaces, and weight should be taken into consideration when selecting a wheelchair to optimize wheelchair quality, rough terrain capabilities, low maintenance, and low cost for the individual.

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