

Development and Results of Wheel Rolling Resistance Testing

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Introduction

Rolling resistance (RR) is the primary force resisting propulsion for manual wheelchair users (MWU). The other two forces-- air resistance & bearing resistance—are considered to be negligible in most cases (Bascou, Sauret, Lavaste, & Pillet, 2017; Hoffman, Millet, Hoch, & Candau, 2003; Vinet et al., 1998). The rolling resistance results from an energy loss of the tire contacting the surface. The material of the tire plays a critical role in the loss of energy due to hysteresis (inelastic deformation), which accounts for almost all of the loss of kinetic energy in rubber (Kauzlarich & Thacker, 1985). Figure 1 shows a free body diagram of the forces. Rolling resistance can be referenced as a force or as a coefficient proportional to the weight: $\mu_{RR} = \frac{F_{RR}}{W}$.

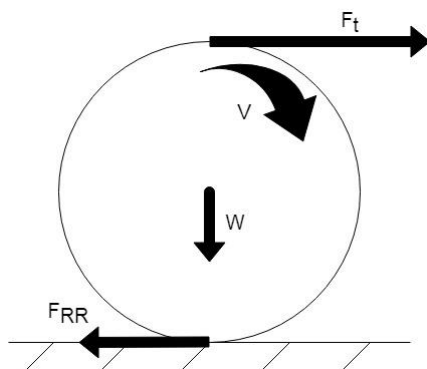


Figure 1: Rolling Resistance Free Body Diagram
F_t is the tangential force, V is angular velocity, W is the load on the axle, F_{RR} is the rolling resistance force.



Figure 2: Drum based rolling resistance testing machine. (1) Drum, (2) Upper Frame, (3) Arm, (4) Truck, (5) Load Cell

For clinicians, it is imperative to understand the biomechanical impact of rolling resistance and related consequences for MWU. Increased RR increases the force required for a MWU to propel their wheelchair, which is linked to an increase in the risk of upper extremity injury and pain, such as rotator cuff injuries (Burnham, May, Nelson, Steadward, & Reid, 1993; Sie, Waters, Adkins, & Gellman, 1992). Injuries and pain can lead to reduced activity and participation (Curtis et al., 1999). Environmental factors such as surface type can also impact propulsion. For example, high pile carpet is harder to propel over as compared to tile. Additionally, changes in rear axle position changes the load on the rear wheels and consequently changes RR (Cowan, Nash, Collinger, Koontz, & Boninger, 2009). Other parameters such as the setup of the wheelchair in toe and camber can affect rolling resistance (VanderWiel, Harris, Jackson, & Reese, 2016). Furthermore, the tire type and tire pressure will also be influential in RR (Sawatzky, Kim, & Denison, 2004).

Learning objectives

1. The background of rolling resistance and previously conducted tests.
2. The biomechanical impact of rolling resistance.
3. The current testing being conducted with rolling resistance and preliminary results.
4. The clinical implications of how wheelchair design parameters impact rolling resistance.

Previous Testing Methods

A scoping literature review on rolling resistance test methods was performed and resulted in 40 articles. These articles were broken down into seven testing method groups including: deceleration, motor draw, treadmill, physiological expenditures, drag tests, ergometer/dynamometer, and robotic test rig. Deceleration testing is when a whole wheelchair goes down a ramp and the distance traveled at the end of the ramp is measured (Frank & Abel, 1989). A drag test pulls the whole wheelchair and measures the force with a load cell (VanderWiel et al., 2016). Motor draw is similar, but it measures the current draw on the motor as it pulls the system (Hillman, 1994). Treadmill testing puts the whole wheelchair on a treadmill and measures the resistive force with a load cell (Claremont & Maksud, 1985). Physiological expenditures testing is when heart rate, oxygen, or instrumented push rims are measured during propulsion (Koontz, Cooper, Boninger, & Yang, 2005). Ergometer and dynamometer testing uses a wheelchair on rollers while measuring a physiological expenditure or forces on the rollers (DiGiovine, Cooper, & Dvorznak, 1997). The last category is a recent invention of a robotic test rig (Teran & Ueda, 2014). However, since only one exists, it is difficult to validate the results. Each test method was evaluated against three criteria: direct or indirect testing method, the ability to test on a component level, and the ability to test multiple setup parameters (camber, toe, tire type, tire pressure, load distribution, and surfaces). The direct test methods are treadmill testing and drag testing. The other five testing methods are indirect and therefore calculate rolling resistance through other measurements and consequently less accurate than direct testing. None of the aforementioned test methods have the ability to test at a component level. Depending on the test design, some have the ability to test a few of the setup parameters, but no one articles tested every setup parameter. Additionally, reporting of results varied greatly with comparative results, force measurements, and coefficients of rolling resistance.

Current Testing

To address the drawbacks of the previous testing methods, a new testing machine was designed and built at the University of Pittsburgh. The effort was guided by members of the International Society of Wheelchair Professionals Standards Working Group (ISWP-SWG). The result is a drum-based testing method shown in Figure 2. The drum (1) is four feet in diameter and rotates at a constant speed. The frame (2) has a top section that holds the arm assembly. The arm (3) is two parallel one-and-a-half-inch precision ground rods that sit tangent to the top surface of the drum. A truck (4) was built to slide on the rods out of four air bushings, with two bushings on either rod. Compressed air is pumped into these bushings, and they float on the rods. Since there is no contact, there is no friction induced into the system. Two plates sit on the truck and allow for toe in and toe out adjustment. On top of the truck is a camber block that can be switched out for different degrees of camber. A load cell (5) is mounted at the front of the arm, with linkage to connect it to the truck. The machine has the capability to test tire type, tire pressure, toe, camber, load, and surface type at a component level. In the future, the machine will be able to test casters as well. When testing, the drum is rotated at a constant speed. The air bearings are released and the truck floats on the rods. Then, the load cell measures the pullback force (F_{RR}) on the truck. The computer filters the load cell signal and outputs μ_{RR} , as well as standard deviation for the trial. The testing is performed at steady state and lasts two minutes total, but only the center 60 seconds are used to ensure steady state.

Preliminary Results

Preliminary tests were conducted to measure change in RR based on three factors. **First**, the load on the system was increased incrementally to see the trend. The results show that when the load on the axle is doubled, rolling resistance doubles, which corresponds to a previous study (Lin, Huang, & Sprigle, 2015). Figure 3 shows these results. With increased loads, rolling resistance increased in a linear proportional trend. **Second**, tire pressure was changed by 20 percent of max inflation (100 psi for the tire used) as show in Figure 4. Tire pressure was tested from 20 percent of max to 120 percent of max with the results being three times higher at 20 percent than 120 percent. A 40 percent decrease in tire pressure resulted in a 44 percent increase in rolling resistance which corresponds with another study (Sawatzky & Denison, 2006). **Third**, toe-in/out was changed in $\frac{1}{2}$ degree increments (Figure 5) and shows an increase in rolling resistance as toe increases. A one degree increase in toe accounted for a 34 percent increase in RR and a 102 percent increase in RR at two degrees. These results are similar to a previous study (VanderWiel et al., 2016). An interesting result is that the half degree value was lower than the zero-degree value. This could be attributed to an error in the system, bearing slop, or a combination of the two.

Weight (lbs)	Mean Force (lbs)
60	0.7955
70	0.946205
80	1.098735
89	1.235788
99	1.412192
109	1.56461

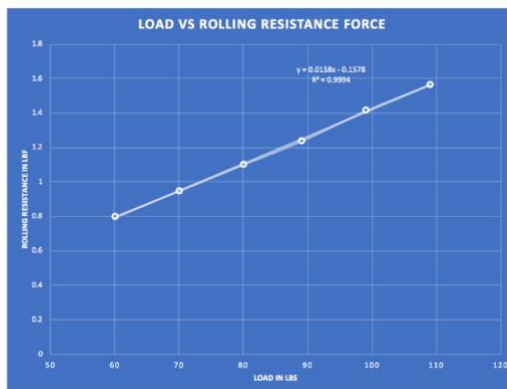


Figure 3: A linear proportional trend between load and rolling resistance

Pressure (% OF MAX (100PSI))	Mean Force (lbs)
20	0.826327
40	0.516975
60	0.410086
80	0.332397
100	0.284003
120	0.250178

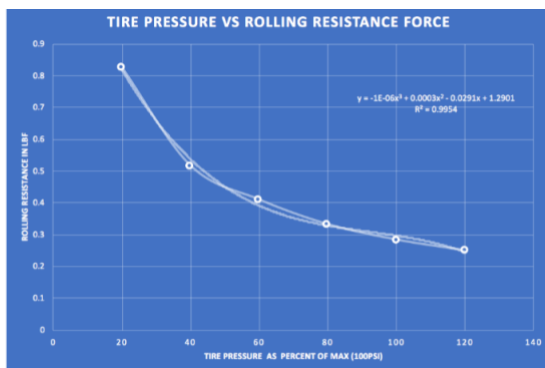


Figure 4: An inverse relationship between tire pressure and rolling resistance.

Toe (Degrees)	Mean Force (lbs)
0	0.78105
0.5	0.689213
1	0.73592
1.5	0.924339
2	1.139652
2.5	1.394435

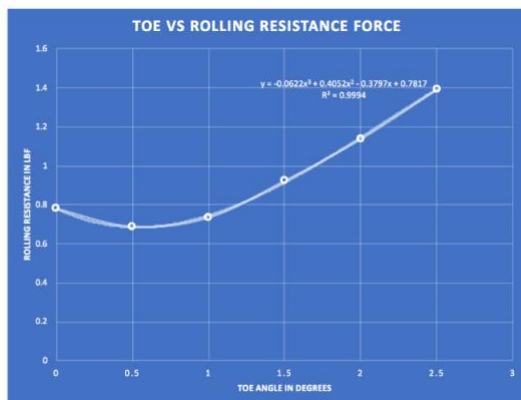


Figure 5: Relationship between toe out and rolling resistance.

Industry Implications

It is important for clinicians to understand the impact of rolling resistance. Wheelchair setup parameters such as rear axle position, tire type, tire pressure, camber and toe can all increase or decrease rolling resistance. Clinicians need to be aware of these and the impact it could have on upper extremities, injuries, and pain. Clinicians will have a reference guide to assess impact, and manufacturers can get feedback on product design and the impact it has to MWUs. The ISWP-SWG is working towards standardization of rolling resistance. This includes the new comprehensive testing machine, and the aforementioned product guidelines to clinicians and manufacturers. As identified in the scoping review, the field does not always report rolling resistance in the same manner and it needs to be standardized as well.

Conclusion

While rolling resistance works against forward propulsion and is impossible to eliminate, it can be managed. Previous testing methods all have drawbacks in their abilities or measurement methods. Our team, with guidance from the ISWP-SWG has developed a new testing machine that can test at a component level and test all necessary parameters. Preliminary results in load, tire pressure, and toe show promising results for the capability of the new machine. These results are important to clinicians to ensure upper extremity injury prevention. Furthermore, manufacturers could use the machine to find lower rolling resistance products for manual wheelchair users.

ACKNOWLEDGEMENTS

The paper was supported by the following: National Science Foundation Integrative Graduate Education and Research Traineeship award number IGERT 1144584, Improving Health and Function Through Use of Performance Standards in wheelchair Selection Grant #: 90REGE0001-02-00, and U.S. Agency for International Development through Agreement Nos. APC-GM-0068, SPANS-037, APC-GM-0107, and FY19-A01-6024. A special thank you to the ISWP-SWG for their continued support of this research and helpful feedback. Additionally, a thank you to the Human Engineering Research Laboratories for the use of their facility to build the testing machine and feedback along the way.

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