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Evaluation of wheelchair tire rolling resistance using dynamometer-based coast-down tests

Andrew M. Kwarciak, MS;[1] Mathew Yarossi, BS;[1*] Arvind Ramanujam, MS;[1] Trevor A. Dyson-Hudson, MD;[1–2] Sue Ann Sisto, PT, PhD[1–3]

[1]Kessler Foundation Research Center, West Orange, NJ; [2]Department of Physical Medicine and Rehabilitation, University of Medicine and Dentistry of New Jersey, New Jersey Medical School, Newark, NJ; [3]Division of Rehabilitation Sciences, Stony Brook University, Stony Brook, NY

Abstract—The objective of this study was to compare the rolling resistance of four common manual wheelchair tires (two pneumatic and two airless solid) and the solid tires used on a commercially available force- and moment-sensing wheel. Coast-down tests were performed with a wheelchair positioned on a two-drum dynamometer. Within each of three load conditions, tire type had a significant effect on rolling resistance ($p < 0.001$). The pneumatic tires had smaller rolling resistances and were less affected by load increases than the solid tires. Within the two tire types, higher air pressure or firmness and lower profile tread corresponded to less rolling resistance. Wheelchair users, clinicians, and researchers must consider the effect of tire type on wheelchair rolling resistance when selecting a manual wheelchair tire.

Key words: coast-down test, dynamometer, inflation pressure, manual wheelchair, pneumatic tire, rehabilitation, rolling resistance, solid tire, tire type, wheeled mobility.

INTRODUCTION

Selection and maintenance of wheelchair tires is crucial to helping manual wheelchair users maximize their wheeling efficiency. One of the most important factors to consider when selecting a tire is its rolling resistance. Rolling resistance is the force opposing the motion of a tire as it rolls across a surface. The main cause of rolling resistance is inelastic deformation of the materials comprising the tire and/or the surface [1]. The amount of deformation is determined primarily by tire design, material composition, laden weight, and surface interactions such that, for a given surface, decreasing the hardness (or inflation pressure) of a tire and/or increasing its laden weight will increase deformation and thus increase rolling resistance [1–3].

Kauzlarich and Thacker presented a set of equations to determine the rolling resistance of a wheelchair tire using a material-based analysis [1]. Other studies have determined rolling resistance experimentally using treadmill drag tests [3–5] or coast-down tests [6–7]. Throughout these experiments, pneumatic wheelchair tires have exhibited lower rolling resistances than solid airless tires. Even at 50 percent of their recommended inflation pressure, pneumatic tires have been shown to roll farther than solid tires [6].

Despite the advantages of pneumatic tires, including improved ride comfort [5], solid tires are still used by many manual wheelchair users. Solid tires require relatively no

Abbreviations: CDD = coast-down distance, MANOVA = multivariate analysis of variance, SD = standard deviation.

[*]Address all correspondence to Mathew Yarossi, BS; Kessler Foundation Research Center, 1199 Pleasant Valley Way, West Orange, NJ 07052.
Email: myarossi@kesslerfoundation.org
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maintenance, short of replacement, and have no risk of puncture or becoming flat. For these reasons, solid tires are also commonly used on instrumented wheelchair wheels that measure the forces and moments applied to the pushrim during manual wheelchair propulsion [8–10]. One example is the SmartWheel® (Three Rivers Holdings, LLC; Mesa, Arizona), a commercially available force- and moment-sensing wheel that comes standard with a full-profile solid tire (Alshin Tire Corporation; Rancho Cucamonga, California). The SmartWheel has been used in multiple research studies [10–12] and is becoming more popular as a clinical tool for objectively evaluating manual wheelchair propulsion [13]. Despite the benefits of the SmartWheel and other instrumented wheelchair wheels, the use of solid tires may affect their ability to obtain representative measurements of wheelchair propulsion. Compared with pneumatic tires, solid tires are less efficient; thus, measurements obtained from instrumented wheels equipped with solid tires may be skewed toward less efficient propulsion. The relative impact of solid tires is not fully known since previous studies have not tested the types of solid tires used on instrumented wheels nor have they tested a variety of commonly used tires under multiple load conditions [5–6].

Given the limited information on the rolling resistance of wheelchair tires, additional investigation is needed. Therefore, the purpose of this study was to determine the rolling resistance of four commonly used manual wheelchair tires and the Alshin tire used on the SmartWheel through dynamometer-based coast-down tests. Unlike previous coast-down tests that were performed overground [6–7], coast-down tests for this study were performed on a two-drum dynamometer, described elsewhere [14]. Dynamometer-based testing has been used in studies of manual wheelchair propulsion [9,15–17] and offers an advantageous environment for coast-down tests. With the wheelchair fixed to a platform and only the rear wheels resting on the drums, the dynamometer setup eliminates the effects of caster rolling resistance and aerodynamic drag and provides a consistent test of rear tire rolling resistance. Based on the results of previous studies [5–6], we hypothesized that the pneumatic tires would have significantly lower rolling resistance than the solid airless tires.

METHODS

Five different sets of tires were tested: (1) Primo V-Trak pneumatic tires (Gallop Cycle Corp; Long Beach, California), (2) Primo Orion pneumatic tires, (3) KIK Mako solid tires (Amerityre Corp; Boulder City, Nevada), (4) Cheng Shin pneumatic tires (Cheng Shin Rubber Ind Co, Ltd; Xiamen, China) with solid inserts, and (5) Alshin solid tires. Each set of tires was mounted on a pair of 0.61 m Sunrims SW600 wheels with radial spokes (Hayes Bicycle Group; Mequon, Wisconsin). All pneumatic tires were inflated to the manufacturer's recommended pressure. **Table 1** lists the relevant characteristics and recommended pressure of each tire. The calculation of tire moment of inertia is described in the **Appendix** (available online only).

Each set of wheels was placed on a Quickie GPV rigid-frame wheelchair (Sunrise Medical; Longmont, Colorado; weight: 9 kg, width: 0.46 m, rear wheel camber: 3.5°). The wheelchair was secured over a two-drum dynamometer such that the rear wheels rested on separate drums, allowing for independent wheel rotation (**Figure 1**). A custom mount was fixed to the seat of the wheelchair, and barbell plates (45.4 kg, 68.0 kg, and 90.7 kg) were added to the mount to create three weight conditions. A calibrated force plate (Bertec Corp; Columbus, Ohio) was used to determine the load supported by each rear

Table 1.
Tire characteristics.

Tire	Type	Profile*	Mass† (kg)	Diameter (cm)	Moment of Inertia†
Primo V-Trak	Pneumatic	Low	0.36	59.6	0.025
Primo Orion	Pneumatic	Full	0.64	61.5	0.045
KIK Mako	Solid	Low	0.48	58.8	0.034
Cheng Shin	Solid Insert	Full	1.16	60.9	0.081
Alshin	Solid	Full	0.71	60.1	0.050

*Low refers to tread type C-1025 or similar; full refers to tread type C-63 or similar.
†Includes mass of tire and tube or solid insert (if applicable).

Figure 1.
Test setup for solid-insert Cheng Shin tires and 377.6 N load condition.

wheel under each condition. To minimize wheelchair vibration and shifting on the dynamometer, we only used the right wheel for testing. Thus, the average load supported by the right wheel under each weight condition was 223.6 N, 291.3 N, and 377.6 N, respectively. These loads include the weight of the wheelchair, wheel, test mount, and barbell plates.

The right wheel was manually spun to a tangential velocity of at least 2.0 m/s. Velocity was measured with an encoder fitted to the surface of the dynamometer drum and an oscilloscope (Agilent Technologies, Inc; Santa Clara, California). Once the speed was reached, rotational force was discontinued and the wheel was allowed to coast down to a complete stop. Ten trials were performed for each tire under each load (150 trials total). Spherical reflective markers were placed on the hub and pushrim of the right wheel. During each trial, the movements of the markers were recorded at 120 Hz with a Vicon motion capture system (Vicon; Oxford, United Kingdom).

DATA ANALYSIS

In order to calculate the rolling resistance of each tire from dynamometer-based coast-down tests, we needed to determine the deceleration of the wheel. Markers on the hub (Hub_{xyz}) and pushrim (Rim_{xyz}) were used to calculate wheel deceleration in each trial. These data were chosen over measurements made by the encoder (at a rate of 30 Hz) because the Vicon system provided a higher collection rate. Marker data were filtered with a second-order, zero-phase, low-pass Butterworth filter with a 6 Hz cutoff frequency [18]. The rotation of the wheel between each time point (q) was then determined from the law of cosines:

$$\theta = \cos^{-1}\left(\frac{A \times B}{\|A\|\|B\|}\right), \qquad \textbf{(1)}$$

where $A = \text{Rim}_{xyz}(i) - \text{Hub}_{xyz}(i)$ and $B = \text{Rim}_{xyz}(i + 1) - \text{Hub}_{xyz}(i + 1)$. The rate of wheel rotation, or angular velocity, was calculated by dividing the change in angle by the change in time for each frame. To account for differences in wheel size, we converted angular velocity to linear velocity by multiplying angular velocity by wheel radius. All trials were required to include the same range of linear velocities; therefore, data were trimmed to those points that corresponded to linear velocities between 1 and 2 m/s. A line was fit to the linear velocity (v) data to determine the deceleration of the wheel (a_d):

$$v = a_d t + v_0 \quad , \qquad \textbf{(2)}$$

where t is the time to coast down from 2 m/s to 1 m/s and v_0 is the initial velocity of the wheel (1.99 ± 0.01 m/s). Goodness-of-fit was determined by calculating the coefficient of determination (R^2) for each linear regression. Overall, the linear regressions accurately represented the data (mean R^2 = 0.998, range: 0.960–0.999).

The calculation of rolling resistance was based upon a model of wheelchair propulsion on an inertial roller system presented by Cooper [19]. To simplify the model, we assumed aerodynamic drag, wheel and roller bearing resistances, and variable external resistances were negligible. The resulting equation of rear wheel motion is

$$T_w = (I_r \frac{R}{r} + I_w)\alpha_w + F_{\text{RR}} R \quad , \qquad \textbf{(3)}$$

where T_w = the torque applied by the hand to the rear wheel; I_r and I_w = the moment of inertia of the roller and the rear wheel, respectively; r and R = the radius of the roller and the rear wheel, respectively; a_w = the angular acceleration of the rear wheel; and F_{RR} = the rolling resistance force.

Since the equation is being used to describe the rotation of the rear wheel once propulsive force has been discontinued, T_w is equal to zero and a_w represents the angular deceleration of the wheel. The moments of inertia of the roller (0.87 ± 0.15 kg-m^2) and the wheels (0.12 ± 0.02 kg-m^2) were determined experimentally using the acceleration method described by DiGiovine et al. [20]. A detailed description of the experimental calculations is provided in the **Appendix** (available online only). By substituting the values of I_r and r (0.16 m) into **Equation 3** and rewriting a_w as linear deceleration divided by radius (a_d/R), we calculated rolling resistance force from the wheel radius, inertia, and deceleration:

$$F_{RR} = \frac{-a_d}{R^2}(I_w + 5.47R) \quad . \qquad \textbf{(4)}$$

The rolling resistance of each tire under each load was represented by the mean F_{RR} of all 10 trials ± 1 standard deviation (SD). A pair of one-way analyses of variance were performed to compare the rolling resistances across tire type (pneumatic and solid) and tire profile (low and full) within each load, assuming independence between coast-down trials within each tire. A repeated measures multivariate analysis of variance (MANOVA) was performed to compare the effect of load on rolling resistance. Statistical analyses were performed using SPSS software (SPSS Inc; Chicago, Illinois) with significance set to $p < 0.05$.

In order to compare our results with those of Sawatzky et al. [6], we also made calculations of coast-down distance (CDD). CDD was computed using the equation of motion in which acceleration is assumed to be constant:

$$\text{CDD} = \frac{1}{2}a_d t^2 + v_0 t \quad , \qquad \textbf{(5)}$$

where t is the time to coast down to a complete stop; therefore, CDD represents the entire coast-down of the wheel (for better comparison of results) and not just the 1 to 2 m/s range over which the calculation of F_{RR} was based. Coast-down time was calculated from **Equation 2** by setting velocity equal to zero and substituting the values of a_d and v_0. All calculations were performed using custom programs developed in MATLAB (The MathWorks, Inc; Natick, Massachusetts), and all data are presented as mean ± SD.

RESULTS

Figure 2 shows the mean rolling resistance force for all five tires as computed from **Equation 4**. Given the small SD (0.13 N) within each set of trials, no error bars were included. Under each load, the pneumatic tires had significantly less rolling resistance than the solid airless tires ($p < 0.001$) and the low-profile tires had significantly less rolling resistance than the full-profile tires (p £ 0.006). Pairwise comparisons within the MANOVA revealed significant differences in rolling resistance between all tires across all loads ($p < 0.001$). The MANOVA also revealed a significant interaction between rolling resistance and load ($p < 0.001$), confirming the distinct effect of each load condition.

To determine the relative differences between the tires, we performed individual comparisons within tire type (pneumatic and solid) and tire profile (low and full). Between the pneumatic tires, the mean rolling resistance of the Primo Orion was 11.0 ± 1.3 percent greater than the Primo V-Trak. Between the solid tires, the mean rolling resistance of the Alshin was 36 ± 10 percent greater than

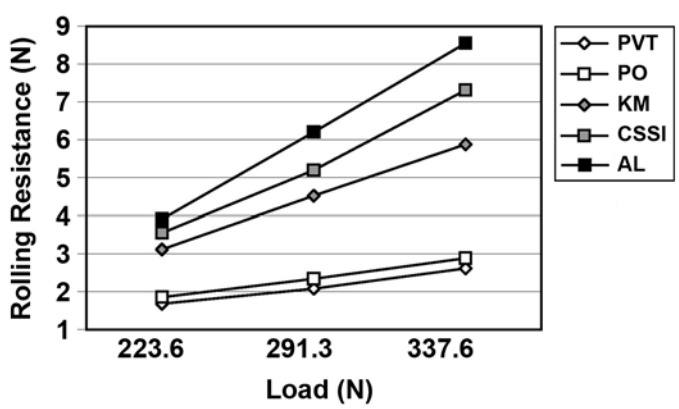

Figure 2.
Mean coast-down deceleration for each tire under each load. AL = Alshin, CSSI = Cheng Shin with solid insert, KM = KIK Mako, PO = Primo Orion, PVT = Primo V-Trak. Diamond markers indicate low-profile tires and square markers indicate full-profile tires.

the KIK Mako and 15.0 ± 4.8 percent greater than the solid-insert Cheng Shin. On average, the rolling resistance of the solid-insert Cheng Shin tire was 18.0 ± 5.7 percent greater than the KIK Mako. Within profile, the mean rolling resistance of the low-profile solid KIK Mako tire was 109 ± 21 percent greater than the low-profile pneumatic Primo V-Trak. For the full-profile tires, both the solid-insert Cheng Shin and solid Alshin tires had rolling resistances that were at least 91 percent greater than the pneumatic Primo Orion tire. The mean rolling resistances of the Cheng Shin and Alshin tires were 122 ± 31 percent and 157 ± 44 percent greater than the Primo Orion tire, respectively.

Across the three loads, the pneumatic tires were more resistant to the effect of load, exhibiting a more moderate change (lesser slope) in rolling resistance. The average increase in rolling resistance for both pneumatic tires was 25 ± 1.4 percent. On the other hand, the solid tires were more prone to the load effect and exhibited larger, more variable increases in rolling resistance. Between the 223.6 N and 291.3 N loads, rolling resistance increased 45 percent for the solid KIK Mako tire, 46 percent for the solid-insert Cheng Shin tire, and 59 percent for the solid Alshin tire. Between the 291.3 N and 377.6 N loads, rolling resistance increased 30 percent for the solid KIK Mako tire, 41 percent for the solid-insert Cheng Shin tire, and 38 percent for the solid Alshin tire. With the exception of the pneumatic Primo V-Trak tire, all tires exhibited smaller percent changes in rolling resistance between the two higher loads.

CDDs were provided as alternative measures of tire performance during coast-down testing. **Table 2** lists the mean CDD and percent difference in CDD with respect to the Primo V-Trak tire. Across the three loads, the pneumatic tires rolled farther than the solid tires, with the Primo V-Trak tire posting the longest CDD and the Alshin tire posting the shortest CDD. As load increased, the percent difference between the two pneumatic tires was consistent (12.0 ± 1.2%), while the difference between the solid tires and the Primo V-Trak increased from 51.0 ± 5.8 to 62.0 ± 7.4 percent.

DISCUSSION

As expected, tire type had a significant effect on wheelchair tire coast-down. Consistent with previously published findings [5–6], the pneumatic tires exhibited less rolling resistance and had longer CDDs than the solid tires. Between the two pneumatic tires, the Primo V-Trak tire had the smallest rolling resistance and the longest CDD. This is likely because of its higher tire pressure (100 psi vs 75 psi in the Primo Orion) and low, smooth tread (**Figure 3**). The advantage of these tire characteristics was also seen in the solid tire data. The KIK Mako, the hardest solid tire and the only low-profile model, had the smallest rolling resistance and longest CDD of the three solid tires. Although tire hardness (or durometer) was not measured, based on manual pressure, the KIK Mako was assumed to have the highest solid tire durometer, followed by the Cheng Shin tire with the solid insert and the Alshin tire. In terms of rolling efficiency, this makes the KIK Mako preferable to the other two solid tires; however, the rolling resistance of the KIK Mako was at least 1.68 times greater than the 75 psi pneumatic Primo Orion tire and at least 1.86 times greater than the 100 psi pneumatic Primo V-Trak tire.

Across the three loads, the solid tires experienced larger increases in rolling resistance than the pneumatic tires. This is consistent with the results of a study involving

Table 2.
Calculations of mean ± standard deviation coast-down distance (CDD).

Tire	223.6 N		291.3 N		377.6 N	
	CDD (m)	% Difference from PVT	CDD (m)	% Difference from PVT	CDD (m)	% Difference from PVT
PVT	22.83 ± 0.22	0.00	18.48 ± 0.51	0.00	14.65 ± 0.17	0.00
Primo Orion	20.14 ± 0.14	–11.79	15.99 ± 0.14	–13.49	13.02 ± 0.12	–11.11
KIK Mako	12.50 ± 0.30	–45.23	8.65 ± 0.10	–53.22	6.67 ± 0.11	–54.48
Cheng Shin	10.92 ± 0.09	–52.15	7.43 ± 0.09	–59.77	5.28 ± 0.08	–63.95
Alshin	9.89 ± 0.34	–56.68	6.22 ± 0.08	–66.35	4.54 ± 0.09	–68.98

PVT = Primo V-Trak.

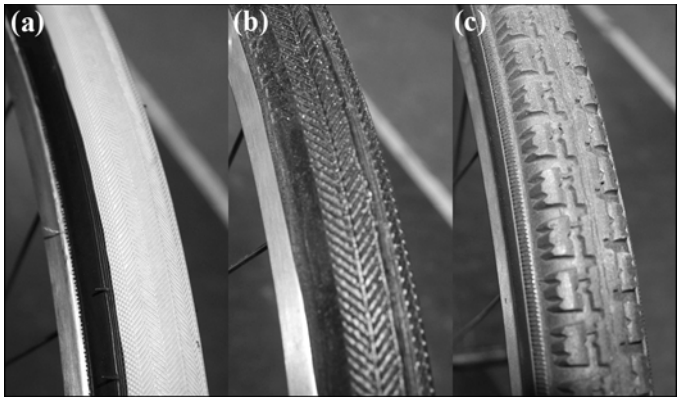

Figure 3.
Tire profiles for **(a)** Primo V-Trak, **(b)** KIK Mako, and **(c)** Primo Orion, Cheng Shin, and Alshin tires (all similar).

treadmill drag testing of several wheelchair tires [5]. In the study, Gordon et al. found that two different polyurethane foam solid tires and a molded polyisoprene solid tire exhibited larger increases in rolling resistance with increased load (ranging from 189 N to 456 N per tire) than a 60 psi pneumatic tire [5]. While our data followed similar trends, the actual values of tire rolling resistance varied. Compared with the results from the 1.33 m/s condition [5], the rolling resistance of the 75 psi Primo Orion tire was 20 to 30 percent lower (across similar load conditions) than the rolling resistance of the 60 psi pneumatic tire. Also, the rolling resistance of the solid Alshin tire was 56 to 72 percent lower than the rolling resistance of the circular polyurethane foam tire. These differences in rolling resistance are likely due to differences in specific tire characteristics (i.e., durometer) and/or the influence of the testing device (dynamometer vs treadmill). Despite the discrepancies, both studies demonstrate the relationship between laden weight, tire type, and rolling resistance. It is important for clinicians and manual wheelchair users to consider that body weight and tire selection both have a significant effect on ease of propulsion. For a heavier individual, the choice of a solid tire over a pneumatic tire will exacerbate the rolling resistance of the wheelchair. This may lead to higher joint forces during propulsion and a greater risk of shoulder injury [21]. For such individuals, a pneumatic tire, or a firm solid tire like the KIK Mako, would be preferable.

With respect to percent differences in CDDs (**Table 3**), our results are comparable to those obtained from an overground study performed by Sawatzky et al. [6]. Under an estimated rear wheel load of 208.7 N (417.4 N for the rear wheels), they found that a wheelchair equipped with 65 psi Cheng Shin tires and KIK Mako tires rolled 12 and 51 percent less, respectively, than a wheelchair equipped with 100 psi Primo V-Trak tires. In our study, under a rear wheel load of 223.6 N, the 75 psi Primo Orion tire and the KIK Mako tire rolled 12 and 45 percent less, respectively, than the Primo V-Trak tire. Both studies demonstrate the ability of the Primo V-Trak tire to roll farther than a lower pressure pneumatic tire or a solid KIK Mako tire for a given coast-down condition. The main difference is that the study conducted by Sawatzky et al. [6] was performed overground; therefore, the data represent the rolling resistance of the entire wheelchair, which is affected by the rear wheels, caster wheels, and aerodynamic drag [7]. Our study used a dynamometer to isolate the rear wheel and reduce the effects of aerodynamic drag; thus, assuming wheel bearing friction to be negligible, our distances represent the rolling resistance of each tire.

In terms of research applications, solid tires may affect measurements of wheelchair propulsion biomechanics. For example, the SmartWheel, which uses the

Table 3.
Comparison of coast-down distance (CDD) across studies.

Tire	Current Study (223.6 N)		Sawatzky et al. (208.7 N)	
	CDD (m)	% Difference from PVT	CDD (m)	% Difference from PVT
PVT	22.83	0.00	10.2	0.00
LPP	20.14	–11.79	9.0	–11.60
KIK Mako	12.50	–45.23	5.0	–50.98

Sawatzky BJ, Kim WO, Denison I. The ergonomics of different tyres and tyre pressure during wheelchair propulsion. Ergonomics. 2004;47(14):1475–83. [PMID: 15697064]
DOI:10.1080/00140130412331290862
LPP = low pressure pneumatic (75 psi for current study and 65 psi for Sawatzky et al.), PVT = Primo V-Trak (100 psi).

solid Alshin tire, is intended to measure the forces and moments applied to the pushrim under normal or near-normal conditions. However, for individuals who normally use pneumatic tires, the Alshin tire presents a relatively high amount of rolling resistance. Compared with that of the full-profile, 75 psi Primo Orion tire, the rolling resistance of the full-profile Alshin tire was 2.11 to 2.97 times greater under the three loads. Participants may account for this added resistance by increasing pushrim force, lengthening pushrim contact, or increasing push frequency. Participants may also alter their normal stroke pattern or the path of the hand throughout the stroke [17]. Without knowing how the adaptations in propulsion are made, some desired observations may be obscured. Furthermore, data obtained from wheels with solid tires may lead clinicians and researchers to underestimate the propulsive capability of the individual under evaluation. Individuals who can achieve a functional velocity in a wheelchair with pneumatic tires may not be able to maintain the same level of function with solid tires. In order to obtain the most accurate measure of propulsion, the testing equipment should mimic the participants' nominal setup. Although this is typically not possible, efforts should be made to optimize the modifiable components of the equipment, particularly tires, when evaluating manual wheelchair propulsion. Researchers and clinicians should consider using tires that best represent the tires used by their participants as well as the potential impact of tire type on manual wheelchair propulsion.

LIMITATIONS

For convenience, a limited number of tires were tested in this study. Inclusion of additional tires may provide more insight into the effects of different pressures, materials, and tire tread designs on rolling resistance. Future studies of wheelchair tires should include additional, newer tires; involve a variety of surfaces and environmental conditions; and explore the effect of tire type and tire maintenance on propulsion biomechanics. In addition, surveys of manual wheelchair users regarding tire selection and satisfaction are warranted. This information would provide insight into the factors involving prescription practices and user preferences. Finally, because of the differences in the testing protocols and the tires, direct comparisons to data presented in previous studies were not possible, although proportional comparisons revealed similar trends.

CONCLUSIONS

Pneumatic tires exhibited lower rolling resistance than solid tires in dynamometer-based coast-down tests. Within the two groups, lower profile tread and higher pressure or hardness corresponded to lower rolling resistance. As load increased, solid tires experienced larger increases in rolling resistance than pneumatic tires. Given the results of this and previous studies, clinicians and wheelchair users should carefully consider the advantages and disadvantages associated with each of the different tire types before choosing a manual wheelchair tire. Researchers should also consider the rolling resistance of solid tires and how their use may effect measurements of wheelchair propulsion.

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Author Contributions:
Study concept and design: A. M. Kwarciak, M. Yarossi.
Acquisition of data: A. M. Kwarciak, M. Yarossi, A. Ramanujam.
Analysis and interpretation of data: A. M. Kwarciak, M. Yarossi, A. Ramanujam, T. A. Dyson-Hudson.
Drafting of manuscript: A. M. Kwarciak, M. Yarossi.
Statistical analysis: A. M. Kwarciak, M. Yarossi.
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