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Rolling resistance of casters increases significantly after two years of simulated use

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Abstract

Introduction: Manual wheelchair propulsion is associated with upper limb pain and injury, and clinical guidelines recommend minimizing propulsive force to lower health risks. One of the strategies to reduce propulsive force is by minimizing rolling resistance (RR). Product testing studies suggest that RR of casters is affected by wear and tear which could have implications on the health risk of wheelchair users. The study will investigate the relationship between caster RR and environmental exposure using standard testing protocols.

Methods: RR of ten casters representing a range of diameters for different models of wheelchairs were measured before and after environmental exposure that includes corrosion, shock and abrasion simulating two years of community use.

Results: Four casters exhibited failures during durability testing, one catastrophically. Increases to RR after corrosion, shock and abrasion exposure were statistically significant using mixed-effects modeling, and four casters had increased RR greater than 20%.

Conclusions: Many of the casters evaluated exhibited increased RR forces and failure after environmental exposure. Improved caster design and use of corrosion resistant materials may reduce these failures. In addition, modification of the provision process could include replacement casters to reduce failures and avoid breakdowns that leave manual wheelchair users stranded or injured.

Keywords

Wheelchair, caster, corrosion, durability, standards, rolling resistance

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Introduction

Globally, over 75 million individuals need a wheelchair for mobility which helps them to participate in activities of daily life and attend school, work and social activities as well as access healthcare.[1] Long term manual wheelchair (MWC) use can lead to upper limb pain and injury.[2,3] For example, two thirds of manual wheelchair users (MWU) with spinal cord injury (SCI) report shoulder pain[4] and the prevalence of MWU's with shoulder pain increases with time.[2,5] Rotator cuff injuries and carpel tunnel syndrome are some of the observed repetitive strain injuries. Chronic pain and subsequent injury can reduce MWUs participation and their ability to complete activities of daily living (ADL). Current practice guidelines suggest minimizing repetitive tasks and high strain activities.[6] However, MWC propulsion contradicts these guidelines due to the repetitive use of UE and high forces when propelling.[7] One of the contributors to high propulsion force is the rolling resistance (RR) of the wheelchair rear wheels and casters.

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RR is the force opposing propulsion and is primarily due to hysteresis and energy losses from rear wheels and casters.[8] Rear wheel and caster selection and wheelchair setup can have a significant impact on the forces required for propulsion,[9] and strategies to optimize or reduce RR can help mitigate high strain and repetitive forces. Failure to reduce RR can place wheelchair users at risk of poor outcomes including injury,[10] and functional limitations.[11]

Rear wheel and caster RR are affected by many factors including tire type, misalignment, camber angle, load and tire inflation.[9,12–14] Several methods have been used to measure RR, including coast-down testing, drag testing, treadmill testing, dynamometer testing, and drum testing.[14–17] Quantifying RR of caster components or factors is difficult with system level tests, and hence, RR testing equipment was developed to accurately measure component level performance (for individual casters) and factors related to RR. This new equipment uses a drum for wheel propulsion, and enables these factors to be simulated and varied for characterization of RR, and is referred to as drum-based testing equipment.[18]

Caster failures are one of the most frequent component failures for wheelchairs.[19] To address this issue, test equipment and methods were developed to reproduce corrosion, shock and abrasion environmental exposures seen in rough terrain wheelchair use.[20] Although caster failures from environmental exposure has been studied, one of the areas that has not yet been investigated is the effect of environmental factors on RR for casters. Wheelchair experts have noted that environmental factors such as shocks, vibrations, dirt ingress, humidity and temperature affect the durability and reliability of wheelchair parts especially rolling elements of casters and rear wheels.[19] Seized bearings, one of the common caster failures, create obstruction for rolling, increase RR and make wheelchairs difficult to propel. Bearing failure is a result of combined effects of heavy loads, corrosion and contamination that occur in adverse outdoor environments found in less-resourced settings and rural areas of resourced settings.[20] Less-resourced settings typically experience tropical climates, rough terrain, dirt and/or dust, and may be encountered in low- and middle-income countries. Whereas resourced environments refer to paved surfaces such as concrete or asphalt that may be encountered in high-income countries. To simulate environmental factors experienced in daily use and outdoor failures, an evidence-based caster testing method was recently developed[21–23] and is under consideration as ISO/CD 7176-32 standard. Casters undergo corrosion exposure in a salt fog chamber followed by shock and abrasion testing on turntable equipment with multiple bumps of varying heights.[21] One of the caster testing studies showed that testing affected the rolling of axle bearings and turning of stem bearings of casters, similar to what was observed in the community.[21] These observations combined with expert feedback from the International Society of Wheelchair Professionals (ISWP) Standards Working Group provided the motivation for specifically investigating the effect of environmental factors on RR in this study.

To that end, this study is focused on understanding the effect of corrosion and shock on caster performance. In addition, this study will potentially identify design and maintenance strategies to optimize RR during wheelchair use and that can be used to refine existing maintenance procedures.[24,25] In addition, the outcomes will help clarify if environmental factors add risk for repetitive strain injuries (RSI). Our research question is to explore if wear and tear on wheelchair casters due to environmental factors impact RR over time. Utilizing the capabilities of the drum-based RR testing equipment and caster testing protocol, the study aims to measure RR for a selection of wheelchair casters before, during, and after simulated environmental exposure. Following are the two study hypotheses to be tested:

1. RR increases significantly after corrosion environmental exposure.
2. RR increases significantly after shock and abrasion environmental exposure.

Methods

The process for conducting the study is outlined in Figure 1.

Caster selection and procurement

Ten casters were selected from seven manufacturers to represent a range of diameters, materials, manufacturers and intended use conditions, including rough terrain often observed in less resourced settings and smooth terrain often observed in resourced settings. Many were selected for their intended use in rough terrain. One sample of each model and its associated bearings were used throughout the testing. Aluminum mounting blocks were used to simulate the caster stem hubs on wheelchairs.

RR testing

Casters were tested with a 30 lb. force load, representing the midpoint of typical caster loading of 20 to 40 lbs.[8,22] The drum surface, simulating a solid propulsion surface, was used throughout all testing at a speed of 1 m/s. Previous testing at multiple speeds showed no change in RR forces, and 1 m/s is representative of

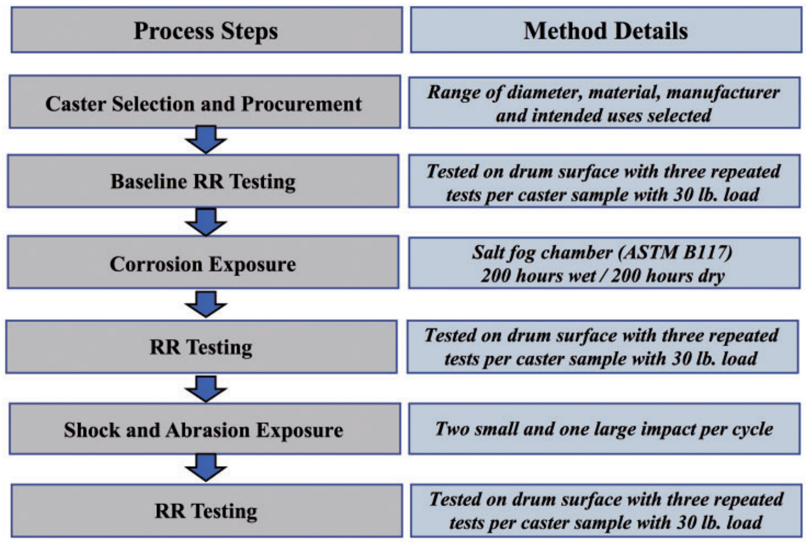


Figure 1. Flowchart of environmental exposure and testing.

manual propel speed.[9] Each test condition was repeated three times for each caster, and results were averaged. Due to limited caster availability and the extended time required for shock and abrasion testing, only 1 sample of each model was tested. Previous studies on multiple samples have shown similar failure outcomes.[22] RR testing equipment shown in Figures 2 and 3 illustrates the equipment set up for casters.

ISO/CD 7176-32 caster testing standard

The standard protocol subjects casters to corrosion and durability testing. Accelerated corrosion testing was conducted in a salt fog chamber with exposure time of 200 hours of wet salt spray and 200 hours of dry cycle, shown in Figure 4. An evidence-based approach was employed to design the caster durability testing method. Community data on road shocks, corrosion, abrasion and caster failures informed the development of the laboratory-based testing method. Accelerations due to road shocks were translated to durability test equipment with appropriate slat height.[21] Number of road shocks observed during the testing were extrapolated to two years of shock exposure since majority of casters fail within 2 years. Testing caster models with a combination of shocks, abrasion and corrosion reproduced real world caster failures.[21] For example, corrosion affected the rolling of bearings. With abrasion, worn-out tire tread and tire cracking failures were observed.

Durability test cycles are outlined in Table 1, with 90% forward and 10% reverse turntable rotations utilized for all caster testing. Durability testing as per the standard includes exposure to shocks and abrasion and is simulated on testing equipment shown in Figure 5.

Figure 2. Drum based RR test equipment.[9]

A 36-grit sandpaper was fastened to the turntable. The speed of the caster on the turntable was 1 m/s. Up to four castors of similar size were tested at one time, and the castors were loaded with 30 pounds of weight. Caster wear was observed in a less-resourced setting and used as a standard to determine the grit of sandpaper best replicating wear to represent one year of use.[21] The standard simulates around two years of

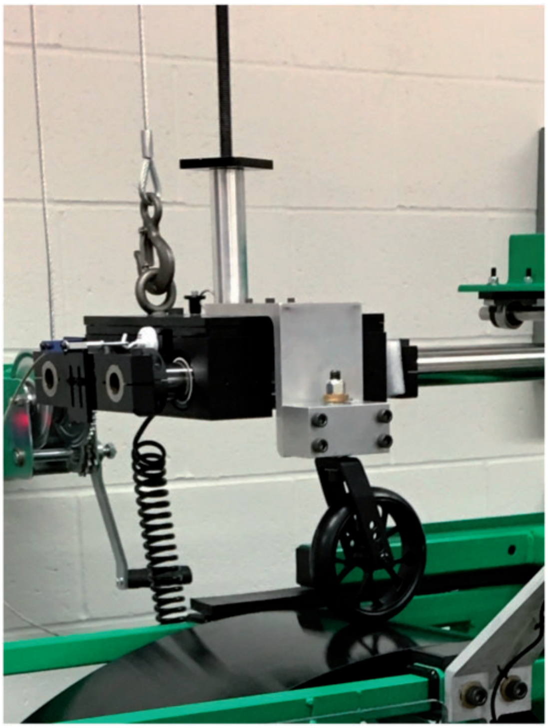


Figure 3. Caster RR test.

Figure 4. Salt fog test equipment for corrosion exposure.[21]

shock and abrasion exposures in the community. Due to limited caster availability and the extended time required for shock and abrasion testing, only one sample of each model was tested. Previous studies on

Table 1. Shock and abrasion testing.[21]

Caster diameter	Slat height (number of slats)	Cycles
$\leq$6 in	0.25 in (n = 2)	6000
	0.5 in (n = 1)	
>6 in	0.5 in (n = 2)	9000
	0.75 in (n = 1)	3000

Figure 5. Shock and abrasion testing equipment.[21]

multiple samples have shown similar failure outcomes.[22]

Statistical analysis

We first examined data descriptively to determine percentage change between baseline, post-corrosion, and post-shock and abrasion timepoints for each caster. Additionally, we examined the number of casters with a percentage change in RR force between post-corrosion and post-shock and abrasion testing. Next, a mixed-effects model was fit using SAS PROC MIXED (SAS software v.9.4), with time (baseline, post-corrosion, post-shock/abrasion) as a fixed effect and a random effect for caster design. Post hoc tests were conducted to examine pairwise comparisons of baseline, post-corrosion, and post-shock/abrasion timepoints. The significance level was set to .05.

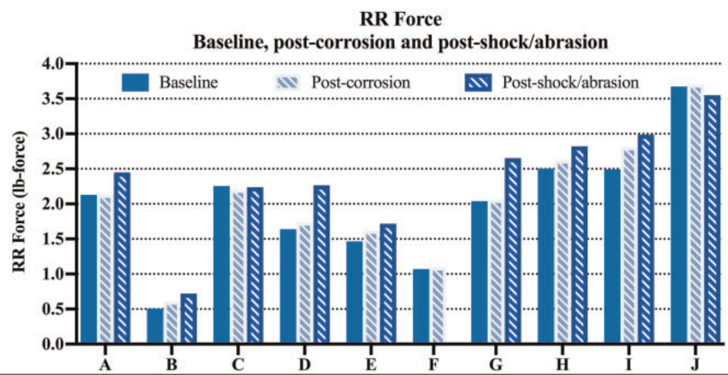
Results

Caster models and respective dimensions are shown in Figure 6. The manufacturer and specific model information is not disclosed.

During shock and abrasion testing, four casters exhibited failures with one failing catastrophically due

Caster Type	A	B	C	D	E	F	G	H	I	J
Diameter (in)	5	6	6	5	7	7.5	7.5	7.5	8	4
Width (in)	1.5	1.5	1.5	1.5	2	2	2	2	1.5	3
Intended Use Environment	rough	paved	rough	rough	paved	paved	rough	rough	rough	rough

Figure 6. Caster models evaluated.



	A	B	C	D	E	F	G	H	I	J
Baseline mean	2.13	0.51	2.26	1.64	1.47	1.07	2.04	2.50	2.49	3.66
Baseline SD	0.028	0.001	0.060	0.047	0.004	0.003	0.040	0.066	0.017	0.012
Post corrosion mean	2.13	0.61	2.20	1.73	1.62	1.09	2.06	2.62	2.81	3.70
Post corrosion SD	0.007	0.003	0.067	0.022	0.055	0.003	0.034	0.034	0.030	0.011
Post shock/abrasion mean	2.45	0.72	2.24	2.27	1.72	Broken	2.65	2.82	2.93	3.55
Post shock/abrasion SD	0.001	0.002	0.075	0.139	0.003		0.042	0.046	0.088	0.006
Post shock/abrasion % change	15%	42%	-1%.	38%	17%		30%	13%	20%	-3%

Figure 7. RR forces at baseline, post corrosion exposure, and post shock/abrasion exposure (mean of three trials) including mean and standard deviation (SD). The percentage change is between baseline and post shock and abrasion exposure.

to a stem bolt fracture. This left nine casters available for caster standard testing. Metal on several of the casters was visibly corroded after corrosion exposure, and caster tread surfaces were visibly abraded and dusty after the shock and abrasion testing, which is consistent with the observed outcomes from previous tests.[19,22] RR forces ranged from 0.51 to 3.66 lb.-force initially, 0.61 to 3.7 after corrosion exposure, and 0.72 to 3.55 lb.-force after environmental exposure. RR forces and percent change between baseline and post shock and abrasion exposure for all casters is shown in Figure 7.

The number of casters with specific percentage changes in RR are shown in Figure 8. In this case, they are grouped by less than 10%, 10 to 20%, or over 20% change in RR due to environmental exposure.

Results of the mixed-effects model showed a significant difference between and within-caster variability in RR. The average baseline RR was 2.03 lb.-force with a significant increase from baseline to post-corrosion ($p < .001$), baseline to post-shock ($p = .015$) and from post-corrosion to post-abrasion and shock ($p < .001$) (see Table 2).

Discussion

The primary study aim was to understand the relationship between RR and environmental factors of corrosion, abrasion and shock. Statistical analysis of RR and caster durability testing results revealed significant increases in RR between baseline, post corrosion, and post shock and abrasion exposure. The increase observed in RR can be due to damage to the bearings and/or changes in caster tread surfaces or caster contact patch caused by abrasion. The changes are significant and could be studied further to evaluate the effect of each individual factor on RR and the increased risk for RSI it places on MWUs. It is worth noting that most casters included in this study were designed for rough terrain.

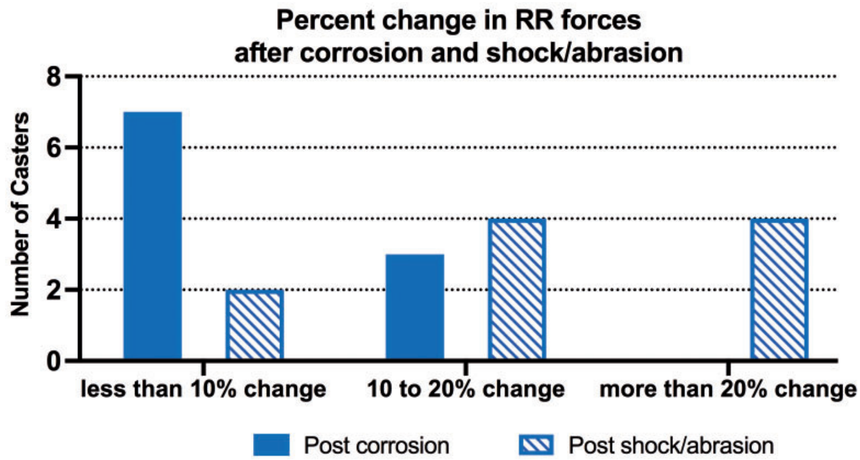


Figure 8. The number of casters with a specific percentage change to RR force post-corrosion and post-shock/abrasion exposure.

Table 2. Mixed-effects model results.

	Estimate	*SE*	*p*
Fixed effects			
Baseline	2.03	0.25	<.001
Post-corrosion	0.08	0.03	.015
Post-shock/abrasion	0.30	0.03	<.001
Random effects			
Intercept	0.68	0.31	.013
Residual	0.02	0.01	<.001

We found that four out of ten casters exhibited some type of failure after caster standard testing which is consistent with previous studies.[26–28] Caster failures have been commonly observed in the community and documented.[26–28] Toro et al found that wheelchair failures can lead to adverse consequences such as stranding, which occurred for 14% of MWC's requiring repair and resulted in missed work, school or medical appointments, or injury, which occurred for 4% of MWC's requiring repair.[26] Other studies report similar results.[27,28] In less resourced settings, stranding episodes and injuries from caster failure may be more challenging for MWU's due to limited availability of maintenance services and replacement parts as well as access to medical care. When considering that an estimated 75 million people globally need a wheelchair for mobility, even low injury rates for manual wheelchairs can lead to significant numbers of injuries and stranding. Reliable and durable casters are very important to the MWU, their participation, ADL and health and these continued failures indicate the need for improved caster designs to ensure that they withstand anticipated use conditions.

Our study considered both percentage difference and total force increases to overall caster RR performance. In our study, the lowest initial RR was from caster B, and although this caster had the highest percentage increase in RR (42%) it remained by far the lowest for RR forces (0.7 lbs.). For caster J, designed for use on rough terrain and having a width of 3 inches, it had the highest RR overall, but RR decreased 3% after simulated environmental exposure. This highlights the importance of considering the total RR forces, as well as percentage changes in RR when assessing caster performance. Significant percentage increases in RR forces were seen for many of the casters.

Risks associated with high forces and repetitive strain for MWU's include chronic upper limb pain and injuries to the rotator cuff or median nerve damage which can lead to carpal tunnel syndrome.[4–7] Injuries to the upper limb can lead to loss of participation and inability to complete ADL, and if the injury is severe and surgery is required, this can cause a temporary loss of mobility or necessitate use of a powered mobility device.[6]

Factors that contribute to RR include caster material type (such as polyurethane or rubber), caster design, contact surface area, and total load on the caster. Bearing drag can also contribute, especially if bearings are corroded or damaged. Increased RR forces after durability could be caused by the roughened caster surface, as well as corrosion or damage to bearings. Both bearing and abrasion performance are important to consider for caster design improvements. However, this study was not designed to separate these effects or to determine predictive factors for caster performance.

The increased RR and high percentage of casters exhibiting failures within two year simulated use indicates most are under-designed. Attention to both design and testing could improve performance and reduce injuries from caster failures and repetitive strain due to high RR propulsion forces. Design improvements could include use of corrosion resistant materials and coatings, and high quality tire materials for increasing damping. There are also hardware and mounting related contributing factors to higher RR, for instance, some designs tested in the study lacked spacing between the fork and bearing hub cap thereby increasing RR. Additionally, bearing slop found in most tested casters can exhibit higher RR than smoother bearings. Such slop widens during use and results in bearing wear down and even fracture.

The results indicate the importance of maintenance and caster replacement before failure. As recommended by the WHO, wheelchair provision in less-resourced settings includes a follow-up step that involves maintenance of wheelchairs. Our results help to emphasize that maintenance steps include replacement casters and bearings to address the frequent failures observed within two year simulated use.

In addition, maintenance procedures should be evaluated and revised to ensure maintenance needs are addressed to avoid increased risk of UE injury and pain. Maintenance can include verifying casters spin freely, checking for bearing and caster component corrosion, tightening fasteners to reduce or eliminate caster bearing slop, and ensuring rear tires are fully inflated. Appropriate wheelchair setup for optimized propulsion biomechanics is also important to confirm, and includes seat height, seat angle and axle position, as well as MWU training on optimized and efficient propulsion methods.

In summary, we observed a statistically significant increase in RR after environmental exposure and we observed one catastrophic failure and three other minor failures in addition to a very wide range of RR. Casters are an important consideration for clinicians, suppliers and MWU's as they choose equipment to provide optimal fit, durability and overall performance while minimizing RR for the MWU.

Conclusion

Long term MWU's frequently experience significant UE pain and injury over time, and clinical guidelines recommend minimizing repetitive strain. Reducing overall RR forces is important and because casters can have a significant contribution to RR, consideration of caster selection and performance is important for MWU's. Our results suggest caster system deterioration and failure as a consequence of environmental exposure causes increased RR. Casters wear down and bearings corrode over time due to environmental factors, and this daily use can increase RR forces for the casters. Design improvements and maintenance guidelines were highlighted as important to optimize RR for casters that can help preserve upper limb function and reduce upper limb pain and injury.

Casters should be designed for their intended environment, such as use on paved or rough terrain surfaces. Design improvements could focus on improved durability and reduced failures, especially catastrophic failures such as stem bolt failures through use of corrosion resistant materials and coatings. Caster tread material could be further investigated to understand optimal material formulations for rough terrain surfaces relative to wear and failure mechanisms. Tread material formulation may be important for damping and shock reduction as well as resistance to abrasion on rough terrain.

Limitations

A limited number of caster models were tested and evaluated in this study and study power could be increased. Durability testing simulating two years is time consuming and destructive to the caster, and due to this, only one caster per type was tested which may limit the validity of our results. Previous environmental exposure studies on multiple sample have shown little variability in failure outcomes[22] which suggest results are likely valid to repeated samples, but this could be a topic of future research. Exposure was limited to a preset order of environmental exposure with corrosion, shock and abrasion that are a subset of environmental factors and do not fully reproduce the environment experienced in the community although both methods were developed through iterative steps to assure external validity.[21,22] Separate evaluation of abrasion and shock may identify the individual contribution of caster surface abrasion and bearing damage on increased RR.

Future work

Further studies should include more casters to increase study power. Including a wide range of casters would be useful to further understand the range of RR forces. A study to evaluate casters frequently used in the community would be useful to validate the results in this study. Further testing could also support caster design, maintenance and standards development related to reducing RR. To separate the factors leading to increased RR after environmental exposure, further testing to isolate change caused by abrasion versus the change from bearing damage is needed. Evaluation of corrosion resistant materials and coatings that could replace traditional options could provide guidance for design improvements. Caster standards development and improvement should be considered to reduce caster failures. Additional loading scenarios could be evaluated for the caster, as they were only evaluated at 30 lbs. of load. This may help characterize and determine casters better suited for heavier or lighter loads and understand a broader range of performance.

Declaration of conflicting interests

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JP.

Contributorship

AM, JO, and JP conceived the study. BK and HWJ conducted testing. HWJ wrote the first draft of the manuscript. CS ran statistical analysis and CS and LT reviewed statistical results. JP secured funding for the study. All authors reviewed and edited the manuscript and approved the final version of the manuscript.

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