UTILIZING COMMUNITY DATA AND LABORATORY TESTING TO RAISE THE QUALITY OF WHEELCHAIR CASTERS

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John Joseph Fried

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This thesis was presented

by

John Joseph Fried

It was defended on

May 27, 2022

and approved by

Jonathan Pearlman, PhD, Chair and Associate Professor, Department of Rehabilitation Science & Technology

Mark Schmeler, PhD, OTR/L, ATP, Vice Chair for Education & Training & Associate Professor, Department of Rehabilitation Science & Technology

David Brienza, PhD, Associate Dean for Technology & Innovation and Professor, School of Health & Rehabilitation Science, and Professor, Department of Rehabilitation Science & Technology

Thesis Advisor: Anand Mhatre, PhD, Assistant Professor, Department of Rehabilitation Science & Technology

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John Joseph Fried, M.S.

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Wheelchairs are pivotal for the mobility of people with spinal cord injuries and similar diagnoses. According to the World Health Organization, 75 million people need a wheelchair for mobility, access to education, employment, and social engagement. Despite the importance of wheelchairs in the everyday lives of their users, the growing research evidence on field evaluation of wheelchairs and laboratory-based testing has shown that manual and power wheelchairs suffer frequent failures in both high-income and less-resourced settings. The majority of wheelchair failures are suffered by the casters which poses a risk for the wheelchair to tip and the user to fall out of the wheelchair and get injured. To raise wheelchair caster quality, the ISO 7176-32 testing standard was developed. The standard incorporates shocks and environmental factors that affect caster quality. The standard has been validated to reproduce community failures in the laboratory.

The purpose of this thesis is to build further on this validation work and improve caster design, quality, and reliability. Chapter 1 provides background information regarding the need for quality wheelchairs and the current prevalence of caster failure experienced by users. The wheelchair standards research that has preceded and informed the work in this thesis is also detailed. Chapter 2 demonstrates the utilization of ISO 7176-32 and additional large data sets from the community for test validation. Analysis of the data found that tilt-in-space wheelchairs experienced nearly double the rate of high-risk failures as their ultralight counterparts. The study correlates the time-to-failure of wheelchair casters between community and laboratory settings and

informs testing dosage specifically for tilt-in-space wheelchair casters. Chapter 3 focuses on caster design improvements by leveraging the testing capabilities of ISO 7176-32. Caster bearings and plastic bushings were tested until failures according to ISO 7176-32 and bushings were found to be more durable and cost-effective than bearings. Chapter 4 summarizes important conclusions of these chapters and the thesis, as well as the future work required to continue this research. Overall, this thesis highlights how laboratory testing can replicate community outcomes to increase device quality and performance, and ultimately improve user safety and independence.

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Preface

I would like to thank the University of Pittsburgh and all of the fantastic faculty, staff, and students that I have been lucky enough to have met and learned so much from over the past two years. To my committee members, Jon Pearlman, Mark Schmeler, and Dave Brienza, thank you for your continued support and guidance throughout the process of creating this thesis. Your contributions were vital to my understanding of the field and this work. I especially would like to thank my advisor, Anand Mhatre, for mentoring me since I met him as a senior mechanical engineering student at Pitt. It has been an honor and priviledge to work on this project with you, and I will continue to cherish the many skills and lessons you taught me throughout working on this. I also would like to thank my internship supervisor, Molly Eads, from the Western Pennsylvania School for Blind Children, who's perspectives and teachings broadened my knowledge of assistive technology and understanding of the outcomes and underlying causes of this research. To Rich Schein and Mary Goldberg, thank you for being an invaluable resource and guide while navigating this program and research. I would also like to thank Hailee Kulich, who introduced me to this field and program many years ago and continues to be a great friend and role model. Lastly, I cannot thank my family and friends enough for their endless love and support along the way. You all being by my side gave me the perserverance to complete this thesis, and I am incredibly lucky to have you all in my life.

1.0 INTRODUCTION

1.1 BACKGROUND

Wheelchairs are pivotal for the mobility of people with spinal cord injuries and similar diagnoses. According to the World Health Organization, 75 million people need a wheelchair for mobility, access to education, employment, and social engagement (WHO, 2008, 2018). Despite the importance of wheelchairs in the everyday lives of their users, the growing research evidence on field evaluation of wheelchairs and laboratory-based testing has shown that manual and power wheelchairs suffer frequent failures in both high-income and less-resourced settings (Wang, Liu, Pearlman, Cooper, Jefferds, Connor, et al. 2010, Toro et al. 2016, Mhatre, Martin, McCambridge, Reese, Sullivan, Schoendorfer, et al., 2017). About 45-88% of wheelchair users required one or more repairs over a 6-month period (Toro et al., 2016, McClure, Boninger, Oyster, Williams, Houlihan, Lieberman, et al., 2009, Worobey, Oyster, Nemunaitis, Cooper, & Boninger, 2012, Henderson, Boninger, Dicianno, & Worobey, 2020). In the context of less-resourced environments this frequency increases to every 3 months (Rispin, Riseling, & Wee, 2018). In the study done by Toro et al., 64% of wheelchair users needed at least one repair, and roughly 30% of users reported facing adverse consequences including injuries and bruises with 18.2% of these being stranded. 40% of manual wheelchair users reported attempting to complete repairs themselves (Toro et al., 2016). Wheelchair repair times range between 2 weeks to 6 months (Mhatre, A., Pearlman, J., Schmeler, M., Krider, B., Fried., J., 2021). The user must stay in the bed or regular chair which perhaps explains the association between wheelchair failures and outcomes such as pressure sore development, hospitalization, pain, depression, and lower self-perceived health (Hoogaboom, Worobey, Houlihan, Heinemann, & Boninger, 2018).

Of all failures reported for wheelchair parts, nearly one-third are front wheel or caster failures (Gaal et al., 1997, Mair, 2018, Mhatre, Reese, & Pearlman 2020). Recent wheelchair failure data collection studies have found that caster stem bearings fracture within 2 years of use in adverse environments as well as in resourced settings (Mhatre, Pearlman, & Lachell, 2018). These premature and frequent failures of wheelchair casters could be attributed to a lack of quality and/or consideration of their specific environments during product design and testing. Cost-reduction engineering practices in the wheelchair industry may have led to the design and selection of low-cost, substandard caster parts that experience different failure modes including seized bearings, damaged bolts, fractured wheels and forks and worn-out tires and fasteners (Mhatre et al., 2020). Stem and axle bearings are subjected to rapid fatigue and stress as wheelchairs are exposed to corrosion, shocks, high temperatures, and dirt especially during use in adverse environments. Examples of this are shown in Figure 1 below.

Figure 1. Examples of casters that have failed due to corrosion of its components

Bearing fractures can lead to a cascade of high-risk failures with caster stems, bolts, and forks as they experience stresses higher than the ultimate tensile strength of their materials. This can cause the stem to fracture, the wheelchair to tip, and the user to sustain injuries. An example of a failure that can lead to tipping is shown in Figure 2. Of the 109 participants in the study done by Gaal et al., 42% had experienced a tip or fall within the last 5 years, and 27% caused injuries needing medical attention (Gaal et al., 1997). The downward spiral of health outcomes following breakdowns negatively impacts the user’s quality of life and increases the public health burden (Hogaboom et al., 2018, Gaal, Rebholz, Hotchkiss, & Pfaelzer, 1997).

Figure 2. Example of a wheelchair that has tipped over due to failure

1.2 WHEELCHAIR STANDARDS RESEARCH

The ISO 7176 wheelchair standards suite of protocols developed throughout the 80’s and 90’s were steps in the right direction for evaluating and improving wheelchair quality with its development of strength, fatigue, and impact tests (Fitzgerald, Cooper, Boninger, et al., 2001) as seen in Figure 3 below. Though one could assume that quality and performance of wheelchairs would have increased due to the implementation of the standards, this is not necessarily the case. A retrospective study of 246 wheelchairs tested with the standards from 1992 to 2008 found that there were no significant improvements in wheelchair test results during that time frame (Wang et al., 2010). A 2013 study evaluating lightweight wheelchairs found that 7 of the 9 samples failed to pass even the double-drum test (Gebrosky, Pearlman, Cooper R.A., Cooper R., & Kelleher, 2013). This was followed by a 2018 study comparing high-strength aluminum ultralight wheelchairs and found that 5 of the 9 samples did not meet the minimum requirement to pass the current standards, suggesting that manufacturing quality had not made substantial improvements since the adoption of ISO 7176 and ANSI/RESNA (Gebrosky B., Pearlman J., Cooper R., 2018).

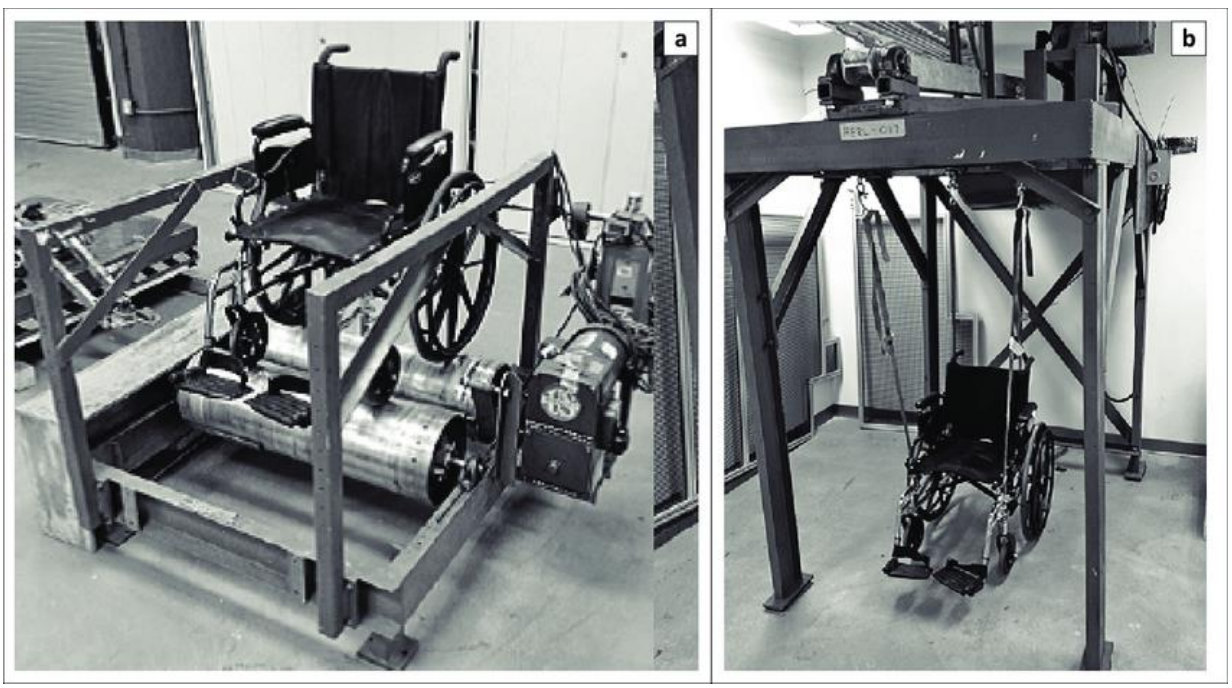

Figure 3. Double-drum test (left) and curb drop test (right)

Less-resourced environments that experience higher temperatures, humidity, dirt, mud, debris, and other factors were notably left out of the development discussion for the original ISO

7176 suite, leading to wheelchairs failing differently and sooner in these environments (Mhatre et al., 2017). A longitudinal study assessing the maintenance condition of wheelchair components in low-resource areas found that casters, footrests, brakes, and seats received low ratings from users despite consistent component replacement throughout the study (Rispin et al., 2018). The Toro et al. study from 2016 also suggested that the current laboratory testing did not necessarily reflect common breakdowns in the community as frame failures are very common outcomes with these standards, but less than 5% of the sample in that study were frame failures (Toro, M., Worobey, L., Boninger, M. L., Cooper, R. A., and Pearlman, J., 2016).

These findings mentioned above made it clear that the exclusion of outdoor environmental factors in standard testing was influencing wheelchair performance and quality and leading to frequent and dangerous failures. Motivated by the high rates of caster failures in the community, the standards working group of the International Society of Wheelchair Professionals (ISWP) and a team at the University of Pittsburgh Department of Rehabilitation Science & Technology led the development of the ISO 7176-32 Caster Durability Testing Protocol (Mhatre et al., 2020, Mhatre et al., 2017, Pearlman et al., 2008, Kim & Muholland 1999, WHO, 2008). A review of literature regarding ISO standard development along with expert advice from members of the ISWP-SWG indicated that specific tests for corrosion resistance, rolling resistance, and durability of whole wheelchairs, caster assemblies, and rear wheels were required to improve the current state of wheelchair quality (Mhatre et al., 2017). Through community data collection and an iterative design process, ISO 7176-32 was developed using both a salt fog exposure chamber to simulate corrosion as well as a shock and abrasion simulator called ISWP Chakra (Mhatre, Ott, & Pearlman, 2017). Both can be seen in Figure 4. The testing protocol is listed in Table 1.

Figure 4. ISWP Chakra (left) and the salt-fog chamber (right)

Table 1. ISO 7176-32 caster testing protocol simulating one year of outdoor use

Exposure	Testing Cycles for One Year Exposure	Slat Height	Number of Slats	Speed	Direction of Turntable rotation
Shock testing protocol for casters less than 75 mm in diameter.					
Low Magnitude Shocks and Abrasion	3000 turntable rotations	6.4 mm	n = 3	1 m/s	Forward (2700) Reverse (300)
Shock testing protocol for casters greater than 75 mm and less than 150 mm in diameter.					
Low Magnitude Shocks and Abrasion	3000 turntable rotations	6.4 mm	n = 2	1 m/s	Forward (2700) Reverse (300)
High Magnitude Shocks and Abrasion		12.7 mm	n = 1	1 m/s	
Shock testing protocol for casters greater than or equal to 150 mm in diameter.					
Low Magnitude Shocks and Abrasion	4500 turntable rotations	12.7 mm	n = 2	1 m/s	Forward (4050) Reverse (450)
High Magnitude Shocks and Abrasion	1500 turntable rotations	20.0 mm	n = 1	1 m/s	Forward (1350) Reverse (150)

Casters commonly used in the community were tested using this protocol, and results showed that the inclusion of corrosion and abrasion reduced durability between 13% to 100%, changed the failure mode for 75% of the tested models, and that two-thirds of those changed failure modes are associated with increased risk of injury for wheelchair users (Mhatre et al., 2020). Exposing casters to the factors of shock, abrasion, and corrosion through this protocol show that a majority of wheelchair casters have substandard durability. On average, they fail on the standard test that requires casters to complete two-years' worth of equivalent test cycles (Mhatre et al., 2020). The failure modes mostly correlated with models in the lab and in the field. There was a 73% match of leading field failures with caster testing failures, and 90% of the matching failure modes were due to the inclusion of environmental factors (Mhatre, Dissertation 2018). Though certain failure modes were found to be common and match with laboratory failures of the same model, the time-to-failure of these models varied. Equivalent years of casters tested ranged from a few days to 15 years and did not align with anecdotal evidence from the community (Mhatre, Dissertation 2018). This informed adjustments to the protocol, but analysis of a large set of time-to-failure data from the community would be needed to correlate these values further.

The purpose of this thesis is to build further on this work and improve caster quality and reliability. Chapter 2 demonstrates the utilization of ISO 7176-32 and additional large data sets for additional test validation. The study correlates the time-to-failure of wheelchair casters between community and laboratory and informs testing dosage specifically for tilt-in-space wheelchair casters. Chapter 3 focuses on caster design improvements by leveraging the testing capabilities of ISO 7176-32. Caster bearings and plastic bushings were tested until failures using ISO 7176-32 and bushings were found to be more durable and cost-effective than bearings. Overall, this thesis highlights how laboratory testing can reproduce community outcomes to increase device quality and performance, and ultimately improve user safety and independence.

2.0 ANALYZING COMMUNITY-BASED CASTER FAILURE DATA TO IDENTIFY TRENDS IN WHEELCHAIR QUALITY AND MAINTENANCE[1]

2.1 INTRODUCTION

Despite the importance of wheelchairs in the everyday lives of their users, the growing research evidence on field evaluation of wheelchairs has shown that manual and power wheelchairs suffer frequent failures in both high-income and less-resourced settings (Wang et al., 2010, Toro et al., 2016, Mhatre et al., 2017). About 45-88% of wheelchair users required one or more repairs over a 6-month period (Toro et al., 2016, McClure et al., 2009, Worobey et al., 2012, Henderson, et al., 2020). In the context of less-resourced environments this frequency increases to every 3 months (Rispin et al., 2018). Of all failures reported for wheelchair parts, nearly one-third are front wheel or caster failures (Gaal et al., 1997, Mair, 2018, Mhatre, Reese, & Pearlman 2020). Recent wheelchair failure data collection studies have found that caster stem bearings fracture within 2 years of use in adverse environments as well as in resourced settings (Mhatre, Pearlman, & Lachell, 2018). These can be particularly high-risk failures as it causes the user to tip out of their wheelchair and become injured. The downward spiral of health outcomes following breakdowns negatively

[1] A portion of this chapter is published in the manuscript "Community-based wheelchair caster failures call for improvements in quality and increased frequency of preventative maintenance" in Spinal Cord by Anand Mhatre, Jon Pearlman, Mark Schmeler, Ben Krider, and John Fried.

impacts the user's quality of life and increases the public health burden (Hogaboom et al., 2018, Gaal, Rebholz, Hotchkiss, & Pfaelzer, 1997).

Though these studies have greatly contributed to the understanding of poor wheelchair quality and its impact on users, the evidence on caster failures is limited . More evidence on the type and variation of caster failures across different wheelchair models is needed. A large data set of caster failures can enable stronger statistical analysis and extract more insights into the type and frequency of caster failures across model types and manufacturers. Understanding the frequency and modes of failures that are risky for users can inform design, quality testing standards development, part selection, repair, and maintenance strategies, and reduce the incidence of wheelchair failures and health consequences.

To improve wheelchair quality and reduce adverse user consequences, standard testing protocols that are informed by and reflect the trends of failure modes and time-to-failure seen in the community must be utilized to screen for high performing casters and identify casters in need of necessary design changes. The adoption of the caster testing protocol ISO 7176-32 is a necessary step to ensure proper wheelchair performance in the community by incorporating outdoor environmental factors in the testing process, but further testing of the protocol is necessary to improve its external validity. Though failure modes of casters in the community have been matched using collected failure samples and through anecdotal evidence, failure data from the users in the community is crucial to facilitate calibration of the testing protocol's failure modes and time-to-failure.

This study aims to perform secondary data analysis of community caster failures across manufacturers and models of wheelchairs reported in the Wheelchair Repair Registry (WRR) (James, Pramana, Mhatre, Brienza, Pearlman, Karg, et al., 2021) to explore their trends and relationships as well as identify appropriate models to test in the laboratory for time-to-failure calibration. Models identified as appropriate were tested using the ISO 7176-32 protocol to compare failure modes and time-to-failure to what was found from the community data. Following are our study hypotheses:

1. Community wheelchair caster failure modes for similar models are not significantly different between manufacturers.

2. The ISO 7176-32 laboratory and community-based caster failure modes are not significantly different.

3. The ISO 7176-32 laboratory and community-based caster time-to-failure are not significantly different.

2.2 METHODS

2.2.1 Wheelchair Caster Failure Data Analysis

2.2.1.1 Description of the Wheelchair Repair Registry

The WRR is a wheeled mobility device failure and repair registry developed by the Rehabilitation Engineering Research Center (RERC) at the University of Pittsburgh from wheelchair repair claims. The claims were reported by repair technicians from a network of wheelchair suppliers using a repair data collection software. Currently, the registry has over 60,000 repairs conducted on more than 5,000 wheelchair devices from 25 manufacturers. The devices include 60% power wheelchairs, 35% manual wheelchairs and 5% scooters. The development and structure of the

WRR and the description of repairs and failures are published elsewhere (James, Pramana, Mhatre, Brienza, Pearlman, Karg, et al., 2021).

2.2.1.2 Data Selection and Analysis

Wheelchair models in the WRR were assigned Healthcare Common Procedure Coding System (HCPCS) codes found on respective wheelchair order forms. Manual wheelchair models were named based on their feature or functionality. For each model, the number of casters (left and/or right) and failures were computed. Caster repairs and failures reported for all manual wheelchair manufacturers and their models beginning in January 2017 until October 2019 were selected for data analysis. The analyzed caster failure types were classified based on the associated risks of wheelchair user injury and damage to other wheelchair parts (Mhatre et al., 2019). Caster wheel fracture and bent parts were designated as high-risk failures while bearing failure and worn-out tires were designated as low-risk failures. Duplicate or missing ticket and failure entries were discarded. Models with 100 caster failures or greater in total were selected for analysis. Based on these findings, caster failures analyzed with traceable purchase and failure dates were chosen to calculate community time-to-failure values. Chi-square tests for independence were conducted to test hypothesis 1 and evaluate the relationship between failures and wheelchair models and between failures and manufacturers. Significance was set at $\alpha = .01$ and statistical analyses were performed manually.

2.2.2 ISO 7176-32 Time-to-failure Validation and Data Analysis

Appropriate casters were identifed from community data for the validation experiment. The failures were grouped by caster, fork, and stem configurations. Casters were selected based on sample size and distributions of high-risk failures (cracked wheels and bent casters) and low-risk failures (bearing fractures and worn tires). A threshold of at least 10 samples per model and 40% high risk failures was established for caster selection. Five samples of four different models underwent ISO 7176-32 testing. More specifically, each sample experienced 200 hours each of high-temperature, wet and dry salt fog exposure and then repeated the caster durability testing exposure described in Table 1. This protocol was repeated until physical failure of the caster component. The time-to-failure of each test sample was determined by the equivalent cycles completed on the caster durability test. Each round of ISO 7176-32 testing is equivalent to two years of testing exposure. Comparison of the community and laboratory failure data was conducted using chi-squared analysis with $\alpha = .01$ for testing hypothesis 2 and two-tailed unequal variance t-tests with $\alpha = .01$ for testing hypothesis 3.

2.3 RESULTS

2.3.1 Community Data Analysis and Caster Selection

A total of 6470 caster failures and 151 service repairs found from 4 manufacturers and encompassing 5 wheelchair model types were analyzed. Table 2 includes descriptions of manual models analyzed in this study. Table 3 shows the distribution of wheelchair caster failures. Manufacturer names are anonymized using M#. Figure 5 shows the caster failure distribution.

Table 2. Wheelchair model descriptions

Wheelchair Model	Description
Manual wheelchairs	
Tilt-in-space wheelchair	Wheelchairs typically prescribed for less-active users who need seating and positioning support
Ultralightweight wheelchair	Wheelchairs typically prescribed for users with active lifestyle and outdoor mobility needs

Table 3. Distribution of caster failures across wheelchair manufacturers and models

Wheelchair Model	Manufacturer	Type of Failure				Service Repairs	Manufacturer & Failure Type Relationship
		Wheel Fracture*	Bent Part*	Bearing Failure†	Worn-out Tire†		
Tilt-in-space							
	M1	46	17	33	29	15	$X^2(3, N=344) = 13.84$, $p<.01$
	M2	104	8	65	42	10	
Ultralightweight							
	M2	119	21	253	92	70	$X^2(3, N=839) = 15.29$, $p<.01$
	M3	55	30	206	63	56	

* High-risk caster failures
† Low-risk caster failures

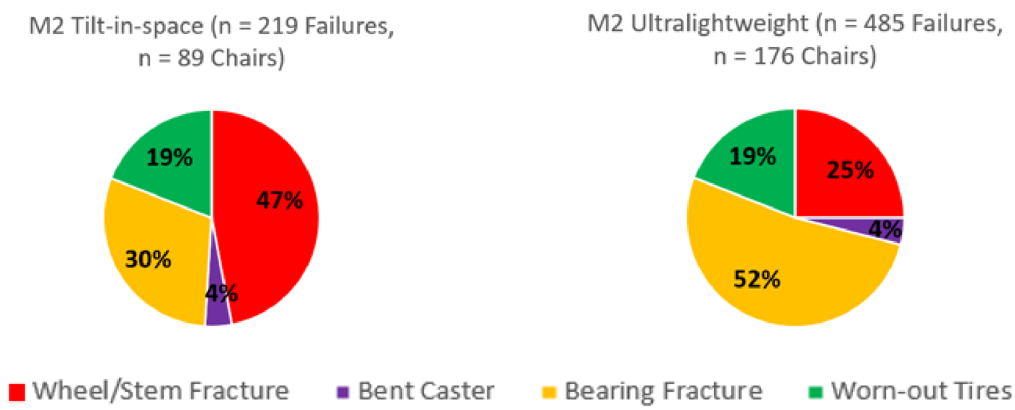

Figure 5. High-risk and low-risk failure trends between manual wheelchair types

For manufacturer M2, the failures were also significantly different between both the manual wheelchair models listed in Table 2, $X^2(3, N=704) = 42.15$, $p<.05$. The tilt-in-space models encountered nearly twice the high-risk failures than their ultralightweight counterparts. Due to this, two different tilt-in-space caster models designed by the manufacturer were chosen for the validation experiment. Caster models greater than sample size n ≥ 10 were selected. Models with at least 40% high-risk failures were selected. The selected casters failure distributions are shown in Table 4.

Table 4. Community failure mode and time-to-failure data

Wheelchair Configuration	Sample Size	Failure Modes and Time-to-Failure (TTF) (Years)							
		Cracked Wheel	TTF	Bent Caster	TTF	Bearing Fracture	TTF	Worn Tire	TTF
Tilt-in-space (6" X 2 Semi-Pneumatic)	N = 58	11	2.36	7	N/A	28	1.99	12	2.02
Tilt-in-space (8" X 1.5 Pneumatic Urethane)	N = 44	16	2.88	6	N/A	8	N/A	14	2.60

2.3.2 Caster testing and comparison

Five caster samples of each model shown in Figures 6 and 7 underwent ISO 7176-32 testing. Failure photos of both caster models can be seen in Table 5 below. Table 6 shows the distribution of failure modes and chi-squared comparison of samples from the community and laboratory. Table 7 shows both the failure mode distributions and average time-to-failure of the tested caster samples. Table 8 compares the failure modes, failure rates, and time-to-failure of community and laboratory testing using a two-tailed unequal variance t-test.

Figure 6. 6" x 2" Semi Pneumatic Tilt-in-space Wheelchair Caster

Figure 7. 8" x 1.5" Pneumatic Urethane Tilt-in-space Wheelchair Caster

Table 5. Caster failure photos for tested models

Wheelchair Configuration	Failure Photos
Tilt-in-space (6” X 2” Semi-Pneumatic)	  

Tilt-in-space (8” X 1.5” Pneumatic Urethane)	  

Table 6. Distribution and comparison of caster failures in community and laboratory settings.

Wheelchair Model	Setting	Type of Failure				Manufacturer & Failure Type Relationship
		Wheel Fracture*	Bent Part*	Bearing Failure†	Worn-out Tire†	
6” X 2” Semi-Pneumatic						
	Community	11	7	28	12	$X^2(3, N=63) = 14.70$, $p<.01$
	Laboratory	0	0	0	5	
8” X 1.5” Pneumatic Urethane						
	Community	16	6	8	14	$X^2(3, N=49) = 7.42$, $p=.060$
	Laboratory	5	0	0	0	

* High-risk caster failures
† Low-risk caster failures

Table 7. Laboratory failure mode and time-to-failure data using the caster testing protocol.

Wheelchair Configuration	Sample Size	Failure Modes and Time-to-Failure (TTF) (Years)							
		Cracked Wheel	TTF	Bent Caster	TTF	Bearing Fracture	TTF	Worn Tire	TTF
Tilt-in-space (6” X 2” Semi-Pneumatic)	N = 5	0	N/A	0	N/A	0	N/A	5	4.99
Tilt-in-space (8” X 1.5” Pneumatic Urethane)	N = 5	5	1.57	0	N/A	0	N/A	0	N/A

Table 8. Comparison of community and lab failure data using two tailed unequal variance t-test

Caster model	Community Data Findings	ISO 7176-32 Test Results	P-Value

	Community Failure Modes	Time-to-Failure	Lab Failure Mode	Lab Time-to-Failure	
8” x 1.5” Pneumatic Urethane	Cracked Wheel (36%)	2.88±0.46 (n=16)	Cracked Wheel (100%)	1.57±0.51 (n=5)	0.014
6” x 2” Semi-Pneumatic	Worn Tire (21%)	2.02±0.57 (n=13)	Worn Tire (100%)	4.99±1.29 (n=5)	.010

2.4 DISCUSSION

Caster failures are unique to each wheelchair manufacturer and model reported in the WRR. The chi-squared analysis produced p-values below $\alpha = .01$ for comparison of wheelchair models from the same manufacturer as well as for comparison of wheelchair manufacturers for the same wheelchair type. Hence, we reject the null hypothesis that community wheelchair models and failure modes would not differ significantly between their respective manufacturers and between models. Comparing the proportion of high-risk failures to total failures among manual wheelchairs, the tilt-in-space models encountered nearly twice the high-risk failures than their ultralightweight counterparts. This trend suggests that users who require a higher level of seating support and have complex rehabilitation needs are at a greater risk of experiencing caster failures that can cause user injury and other adverse consequences. This finding calls for urgent improvements in caster quality.

Next, the testing of tilt-in-space models also provided several key findings related to their failure modes. The 6” semi-pneumatic model consistently failed due to worn tires that inhibited caster function and began to damage the wheel hub. For this model, this was the second most common failure mode from the community data. The chi-squared analysis demonstrated that the failure modes of the community and laboratory samples differ significantly. Hence, we reject null hypothesis 2 for this caster model. Despite this, the protocol does still accurately predict a low-risk failure for this model.

The 8” urethane model failed due to cracked wheel hubs in all 5 samples tested with the protocol. This is consistent with the community data as cracked wheels are also the most common failure reported for this configuration. Chi-squared analysis produced a p-value much higher than $\alpha = .01$, so the hypothesis that the failure modes of the community and laboratory samples would not differ significantly fails to be rejected for this model. The failure mode comparisons on 6” semi-pneumatic and 8” urethane models show that the ISO 7176-32 caster testing protocols demonstrate substantial external validity.

Time-to-failure comparisons offered further conclusions. The lab-tested samples of the 6” caster model lasted significantly longer than seen in the community data. We reject hypothesis 3 that the time-to-failure of community and laboratory samples would not differ significantly for this model. The 8” casters, on average, failed somewhat sooner than the 2-year equivalent cycles required by ISO 7176-32. The hypothesis that the time-to-failure of the community and laboratory samples would not differ significantly fails to be rejected for this caster model. Further caster quality improvements should be made by the manufacturer. The conclusion that one model produced accurate results while the other did not suggest that additional testing validation is required.

This study suggests that further testing protocol improvements should be considered. The variance in outcomes for the models in the community and the laboratory could potentially be attributed to both the testing procedure of the protocol as well as the specific performance characteristics of tilt-in-space wheelchairs. Evaluation of a full tilt-in-space wheelchair should be conducted to determine weight distribution on the casters, integration of the caster with the rest of the wheelchair, use patterns of the users compared to that of ultralight wheelchair users, and other aspects. This could lead to specific testing changes for tilt-in-space wheelchair casters that differentiate the process from ultralight wheelchair caster testing. Furthermore, each wheelchair type could in fact need its own procedure for testing.

2.5 STUDY LIMITATIONS

The WRR data lacks data on wheelchair setup, provision, user training, user- or caregiver-led maintenance, user demographic characteristics, technician training, and use conditions that may influence failure type and frequency. Wheelchairs in use that did not encounter caster failures are not included in the WRR and were not a part of the data analysis. However, a 45-63% failure rate within 6-months of wheelchair use found in previous studies (Toro et al., 2016, McClure et al., 2009, Worobey et al., 2012) can be a suitable reference. Regarding the time-to-failure calibration, the community data is relatively new and after filtering it down to the dataset used for the study, the sample sizes were relatively small. The laboratory sample size was moderate considering testing costs. The distance travelled by the user within each sample's time-to-failure was also not captured in the community dataset, so correlating this value to a distance-based time-to-failure in the laboratory may not be accurate.

2.6 FUTURE WORK

Now that a baseline relationship has been established between the time-to-failure of community and laboratory casters, the next steps should consist of experimentation to eliminate any significant differences between these two sets of values. Full wheelchairs should be acquired if the corresponding caster models had differences between these two results to understand their performance. Qualitative studies on field failures can also be done to analyze the root causes of caster failure and inform more modifications to the testing method. This will allow the authors to develop more accurate procedures for caster testing.

As the WRR data grows and more failure timepoints and purchase dates become available, it will be possible to reliably compute time-to-failure for multiple models and wheelchair parts. Distance travelled by the user should also be recorded in order to get a more accurate comparison to laboratory testing. Studies could be done to track users' distance travelled until failure and then test replicated caster configurations in the laboratory. Laboratory testing could also potentially inform the frequency of preventative maintenance events. If a consistent time to failure for various caster models can be established, studies using ISO 7176-32 could be done to apply preventative maintenance close to predicted failure

2.7 CONCLUSION

Wheelchair caster failures put wheelchair users at risk for multiple consequences, leading to decreased self-perceived health and quality of life. In this study, users who use wheelchair products that provide complex rehabilitation care as well as greater seating and positioning support were found to experience a greater number of high-risk caster failures. Laboratory testing must be used to screen casters and promote high quality designs. Calibrating the failure modes and time-to-failure of this testing method to community evidence is a vital step in adding further validity to the testing protocol, and this study has established the current relationship of these values. Tilt-in-space wheelchair casters have mixed correlations between the community- and lab-based failure modes and time-to-failure. Experimentation with more caster samples using the testing procedure will allow the authors to refine the protocol and further improve the protocol's external validity.

3.0 EVALUATING THE DURABILITY AND COST-EFFECTIVENESS OF BUSHINGS AND BEARINGS FOR WHEELCHAIR USE IN ADVERSE ENVIRONMENTS[2]

3.1 INTRODUCTION

As shown by the analysis of the community data from the previous chapter, bearing failure accounted for 26-58% of all failures experienced by manual wheelchair users. Though these fractures are not an immediate issue to a user, they leave the caster exposed to higher-risk failures, especially if the bearings fail to be replaced in a timely manner. Repair times can range from 2 weeks to 6 months which put users at risk for more dangerous failures like stem fracture (Mhatre et al., 2021) This prevalence of bearing failure aligns with and exceeds reported statistics from community studies and suggests that bearing failure could be even more common than previously thought (Gaal et al., 1997, Mair, 2018, Mhatre, et al., 2020). Bearing fracture has also been commonly seen in the lab preceding more dangerous failures (Mhatre et al., 2017). Recent wheelchair failure data collection studies have found that caster stem bearings frequently fracture within 2 years of use in adverse environments as well as in resourced settings (Rispin et al., 2018). 45-88% of wheelchair casters fail within 6-months of wheelchair use as found in previous studies (Toro et al., 2016, McClure et al., 2009, Worobey et al., 2012, Henderson et al.,

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2020). These premature and frequent failures of wheelchair casters could be attributed to a lack of quality and/or consideration of their specific environments during product design and testing. Cost-reduction engineering practices in the wheelchair industry may have led to the design and selection of low-cost, substandard caster parts that experience different failure modes including seized bearings, damaged bolts, fractured wheels and forks and worn-out tires and fasteners (Mhatre et al., 2020). Stem and axle bearings are subjected to rapid fatigue and stress as wheelchairs are exposed to corrosion, shocks, high temperatures, and dirt especially during use in adverse environments. Such congruent findings from the community and laboratory-based standard testing studies motivated the authors to investigate the bearing designs that may prove to be more effective in the environments in which they are used.

Bearing fractures can lead to a cascade of high-risk failures with caster stems, bolts, and forks as they experience stresses higher than the ultimate tensile strength of their materials. This can cause the stem to fracture, the wheelchair to tip, and the user to sustain injuries. The development of more dependable, low-cost stem and axle bearings for wheelchair casters is crucial to reduce bearing failures and ensure user safety. Thermoplastic bushing materials could be less susceptible to corrosion and wear during operation and provide a possible design improvement for casters which motivated this study (Schweitzer, 2010). More specifically, we sought to compare the performance of traditional caster bearings with thermoplastic bushings and proposed the two hypotheses:

1. Casters with thermoplastic bushings have significantly higher durability than those with traditional ball bearings based on a standardized lab-based test.

2. Thermoplastic bushings are significantly more cost-effective, based on their cost-per-cycle, than traditional ball bearings used on casters.

3.2 METHODS

3.2.1 Selection of Testing Materials

One caster model was selected to be tested with each bearing and bushing model to control and isolate the performance of the bearings and bushings. A standard 8” soft urethane caster model seen in Figure 8, widely used on multiple wheelchair models provided around the world, was chosen for the testing study.

Figure 8. Standard caster used for each bushing/bearing sample

Four models – two bearing models and two bushing models were selected for comparative testing as shown in Table 9. The standard type ZZ caster ball-bearings selected are the bearings supplied by the caster manufacturer. Type ZZ double shielded bearings have unremovable, no-contact metal shields in the outer ring to protect the rolling elements inside and represent a commonly selected low-cost bearing for wheelchair casters in LMICs. The balls of the bearings are covered but not completely sealed, so debris and humidity still infiltrate the bearing. Type 2RS double-sealed chrome steel deep-groove radial bearings were also selected so that the full range of bearing durability could be established in the study for bushing comparison. These type 2RS bearings have a nitrile rubber seal that protects the balls of the bearings from the environment. The bushing materials were selected based on recommendations from wheelchair experts from the ISWP Standards Working Group. Both bushing materials in Table 8 were selected because of their self-lubrication, lower wear rate, low coefficient of friction, resistance to corrosion and chemicals, and low humidity absorption (Schweitzer, 2010). The two manufacturers chosen provided samples of the materials that were machined to the bearing dimensions with press-fit tolerances recommended by the manufacturers.

Sixteen total samples underwent the ISO testing protocol. Unit cost for the bushings were calculated using web calculators from the respective manufacturers and the standard dimensions of the bushings and are listed in Table 9. Dimensions for each stem and axle bearing/bushing are shown in Table 10. An ABEC tolerance rating of 5 or higher (Outer Diameter/Inner Diameter: +.0000/-.0002 in., Width: +.0000/-.0010 in.) was required for each bearing and bushing chosen (ISO 492:2014 Rolling bearings — Radial bearings — Geometrical product specifications (GPS) and tolerance values, 2014). Both bearings had ABEC 5 ratings, and the bushings were machined and verified to be within ABEC 5 tolerances. These tolerances also cover ABEC 7 ratings as well.

Table 9. Bearing/bushing models tested in the study with unit cost

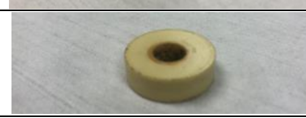
Bearing/bushing Model	Stem Bearing/Bushing		Axle Bearing/Bushing	
	Model	Unit Cost	Model	Unit Cost
Standard type ZZ double-shield deep groove caster ball-bearings		$0.99		$0.99
Type 2RS Chrome Steel Double-sealed deep groove caster ball-bearings		$11.85		$8.88
Thermoplastic Bushing #1		$1.15		$1.15
Thermoplastic Bushing #2		$1.15		$1.15

Table 10. Dimensions for the stem and axle used for each bearing/bushing type

Bearing/Bushing Type	Flange Thickness (in.)	Outer Diameter (in.)	Inner Diameter (in.)	Width (in.)	Dynamic Load Capacity (lbs)	Static Load Capacity (lbs)
Stem	0.062	1.125	.50	.3125	884	501
Axle	N/A	.866	.315	.276	750	315

3.2.2 ISO 7176-32 Caster Durability Testing Protocol

The ISO Caster Durability Testing Protocol, ISO 7176-32, includes corrosion testing in a salt fog chamber (as per ASTM B117) followed by durability testing on ISWP Chakra. Durability testing includes exposure to shock and abrasion. Table 1 previously details the caster testing protocol. Figures 9 and 10 show the corrosion and durability testing conducted with the caster models in this study. The testing was limited to an exposure equivalent to 6 years of wheelchair use as most of these bearings fail within that time in adverse environments and need replacement according to previous work (Mhatre et al., 2017, 2018, 2020). Wheelchairs are replaced by this time as well. Testing of a sample was discontinued following a bearing/bushing failure or caster failure. Durability is determined by the number of shock testing cycles completed in the ISO 7176-32 Caster Durability Testing Protocol. Cost-effectiveness is calculated as a test cycles-per-dollar ratio. The cost included the combined cost of two stem and two axle bearings/bushings.

3.2.3 Data Analysis

One-way ANOVA statistical analysis was performed in SPSS to test the hypotheses. If significance was found, a Tukey post-hoc test was used to reveal where the significance lay within the bearing and bushing models. A significance level of $\alpha=.05$ was used.

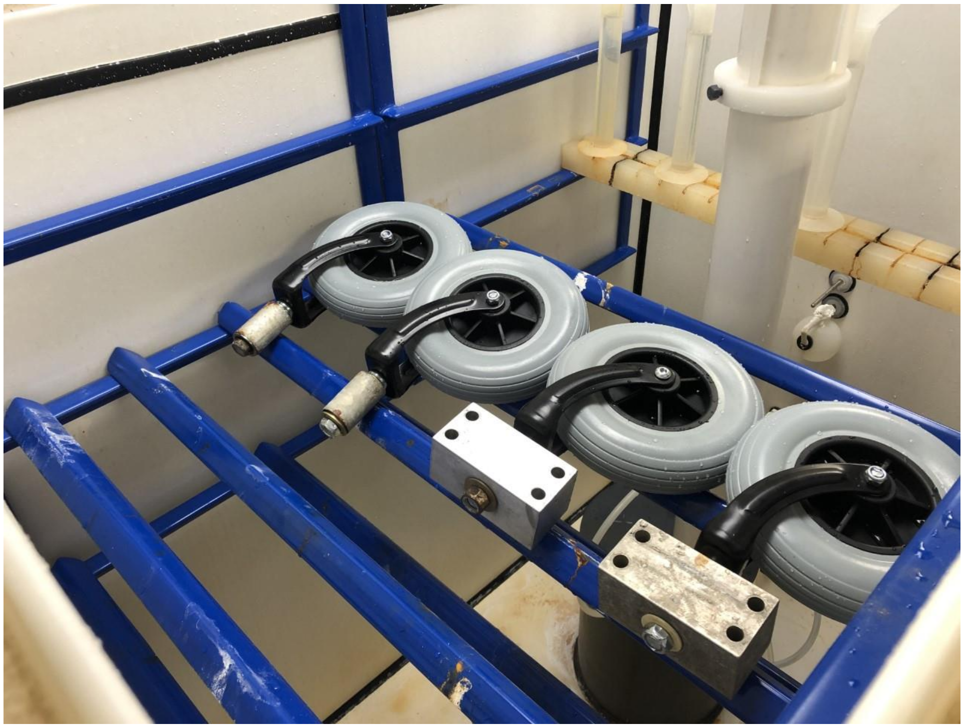


Figure 9. Sample casters undergoing corrosion testing

Figure 10. Sample casters undergoing durability testing

3.3 RESULTS

Failures encountered during testing are shown in Table 11 below. Failure modes are shown in Figure 11. The axle bearings and bushings for all samples did not encounter any failure. Stem bearings as opposed to axle bearings are subjected to thrust forces and since, both are of similar quality, the stem bearings typically experience failures during field use and lab-based standards testing. Most bushing samples either remained intact or exhibited a stem failure, with the stem bushings usually breaking at the flange. The flange intersection with the bearing cross-section experiences the highest stress and hence, it is common to experience flange failures during field use and standards testing (Mhatre et al., 2017, Mhatre et al., 2018, Mahtre et al., 2020). Cycles to failure and cycles/dollar of the bearings and bushings are shown in Figure 12.

There was a significant difference in durability across the models, $F(3,12) = 3.88$, $p=.04$. The Tukey post-hoc test showed that the durability of thermoplastic bushing #2 was significantly higher than the standard double-shield ball bearing, $p<.05$. There was a significant difference in cost-effectiveness across the models, $F(3,12) = 7.64$, $p =.004$. The Tukey post-hoc test showed that the cost-effectiveness of thermoplastic bushing #1 and #2 respectively was significantly higher than the double-sealed bearings, $p<.05$.

Table 11. Stem bearing and stem bushing failure photos

Bearing/bushing Model	Failure Photos		
Standard type ZZ double-shield deep groove caster ball-bearings			
Type 2RS Chrome Steel Double-sealed deep groove caster ball-bearings			
Thermoplastic Bushing #1			
Thermoplastic Bushing #2			

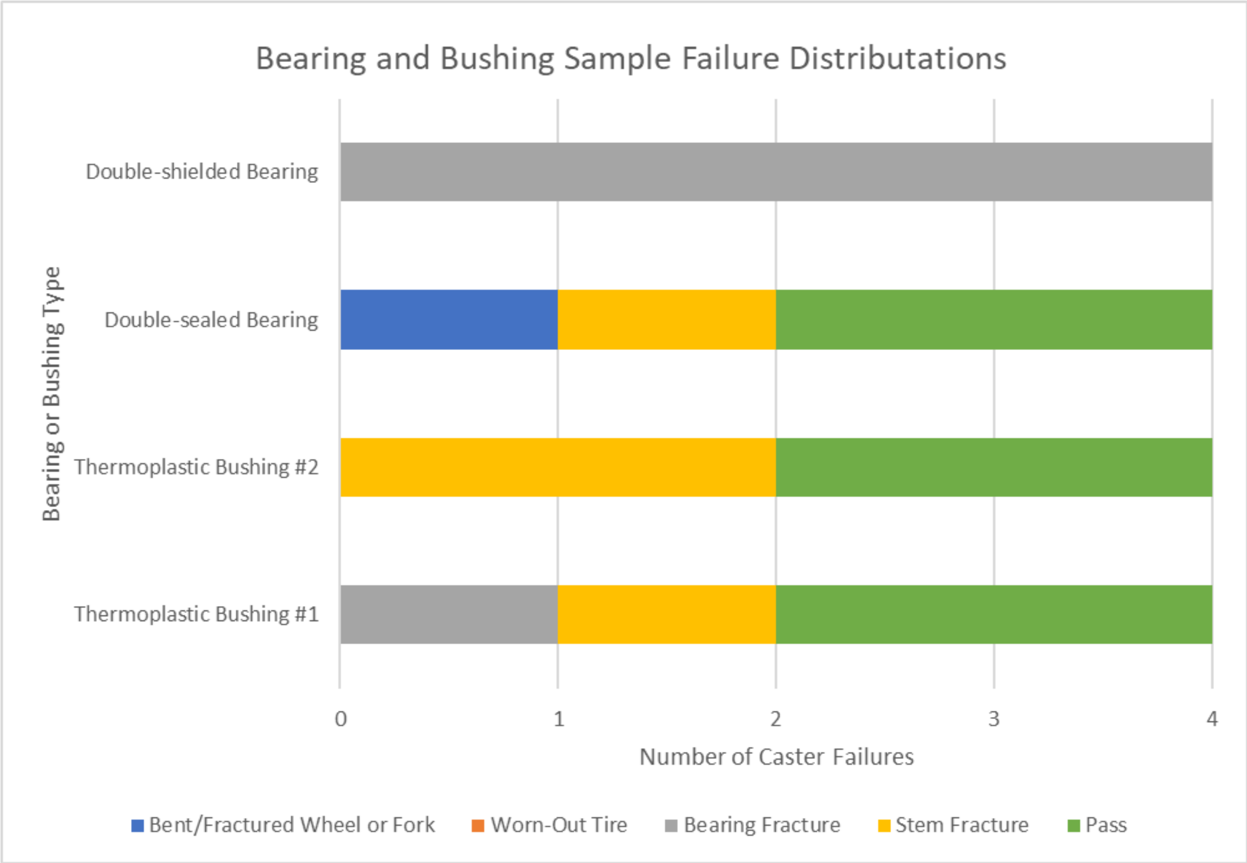


Figure 11. Failure mode distirbutions for each sample tested

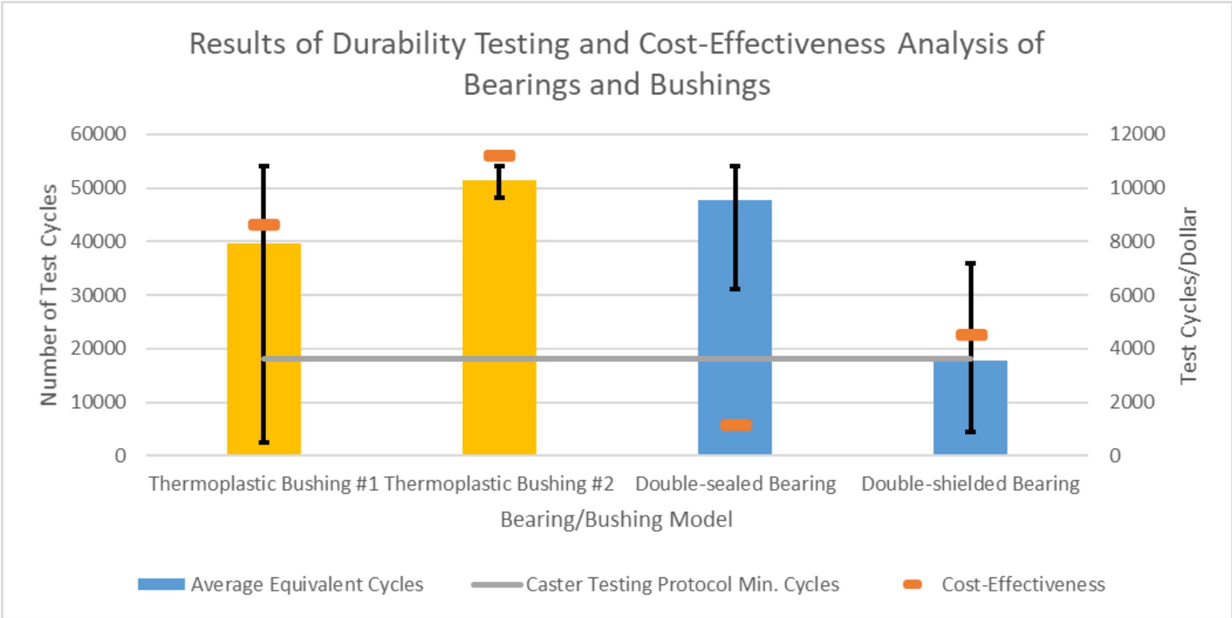


Figure 12. Comparative bearing and bushing testing results

3.4 DISCUSSION

Results from the comparative testing study demonstrate that thermoplastic bushings are viable for use in wheelchairs as they are significantly durable and cost-effective compared to metallic bearings. Though this study focuses on adverse environments, a rolling element that is more durable and cost-effective can benefit users in any environment. Ideal casters for wheelchair application should have a high load bearing capacity and tight tolerances to absorb road shocks and impacts as well as material properties that resist corrosion (WHO, 2008). Thermoplastics are often superior to metals in their corrosion resistance because they are not as easily oxidized due to their strong halogen bonds (Schweitzer, 2010). Hence, these materials were chosen for investigation.

Both thermoplastic bushings lasted beyond the minimum quality requirement of the ISO/DIS 7176-32. As per the study results, samples from both models survived twice the number of equivalent test cycles listed in the protocol with one exception. One sample of thermoplastic bushing #1 failed prematurely in testing at 2,455 cycles, leading to lower durability on average and higher range of results for those bushings. It is difficult to pinpoint why this one-off failure occurred. This could be due to the manufacturing variability in the bushing material or tolerancing of the flange section of the bushing. Such one-off failures are common in product testing and hence, testing of four samples was considered. Other than this, thermoplastic bushing #2 demonstrated the least variation in durability or number of test cycles completed, indicating the consistency of their potential performance and reliability in the community.

On average, the double-shield caster ball-bearings failed to meet the minimum quality requirement of the ISO/DIS 7176-32 which is two-year of simulated outdoor use. These bearings are low-cost bearings that have been shown in previous literature to fail prematurely and are overall unsuitable for less resourced adverse environments (Mhatre et al., 2020). The double-sealed products are used on certain wheelchairs in high-income settings and based on testing results, certainly exceed the strength requirements of a typical manual wheelchair caster bearing. Caster and bearing failures shown in Table 11 are typically encountered in the community and during standards testing.

Resistance to corrosion and related wear improved the longevity of the thermoplastic materials as witnessed in our study. Our results suggest that thermoplastic bushings can be both cost-effective and durable. Additionally, bushings may offer a low-cost alternative because they can be mass produced using processes like injection molding which further reduces the total product cost and improves part availability. The cost-effectiveness was calculated using unit costs, so it is worth noting that the overall price per bushing will most likely decrease when manufactured in bulk. Bushings may also be manufactured using 3D printing technology that is gaining traction in the global assistive technology sector and will further facilitate easy access (ProsFit). These methods are especially important in LMICs where access to wheelchair parts is challenging (Mhatre et al., 2017). Since bearings are typically treated as consumables or parts that frequently require maintenance or replacement, and bushings are cost-effective, a wheelchair provider can include additional bushing samples during wheelchair provision.

The minimal amount of rust on the bushings' surface did not impede its natural wearing and rolling ability. On the contrary, the rusted bearings did experience obstruction to rolling and consistently higher amounts of tire wear in the ball-bearing samples, which is consistent with recent evidence (Wilson-Jene, Mhatre, Ott, Krider, Smith, Terhorst, & Pearlman, 2021). Such obstruction can increase the rolling resistance experienced by the user and lead to poor real-world performance as well as health issues like upper extremity injuries (Wilson-Jene et al., 2021). A future study could be to test the relative increase in rolling resistance of ball bearings versus bushings using these identical methods. If rolling resistance is lower for thermoplastic bushings, it would indicate potential for real-world performance as well as for durability and cost-effectiveness as shown in this study.

This is the first study to compare bearings and thermoplastic bushing materials for application in wheelchairs. The authors plan to conduct further investigation into the design of cost-effective rolling elements and support the wheelchair sector with new knowledge and design innovation. Improved durability of bearings and bushings is vital to raise the quality and performance of wheelchairs in the community and reduce the frequency of wheelchair breakdowns and adverse consequences to the user.

3.5 STUDY LIMITATIONS

Due to the length of time required for testing and cost of testing, the sample size of this study is relatively small. With further testing, addition of testing samples would aid in the validity of the results. The length of time required for testing and usual lifetime of casters and wheelchairs led us to cap the testing at 6 years of equivalent cycles. Both thermoplastic bushing models, as well as the double-sealed bushings, all had samples that survived beyond this mark, but were not tested further. The bushings were manufactured in-house to ABEC 5 tolerance ratings, so potential discrepancies in the machining process could have led to premature failures and underestimated durability for the models tested. Only one type of caster was used in this study to isolate the effect of the bushings and bearings on durability and cost-effectiveness, so the consistency of this effect across different models and users is unknown. Debris infiltration from dust and dirt could also heavily impact both bushings and bearings, so a lack of this type of environmental testing affects the outcome of this study. The cost-effectiveness for the samples was based on unit costs that did not consider savings on large-quantity orders, and therefore our results likely underestimate cost-effectiveness. Though this study has established the quality of these bushings, it did not evaluate its real-world performance. Aspects such as rolling resistance and overall speed were not analyzed in this study and impact the usability of the product by the user.

3.6 FUTURE WORK

Our results suggest that bushings may be a more durable and cost-effective alternative to roller bearings, and therefore reduce the incidence of bearing failure in the community. Along with rolling resistance tests, there are additional environmental conditions that must be examined to fully evaluate bearing and bushing performance as well. Tests for dirt and dust contamination are potential additions to the testing protocol that would help to evaluate the efficiency of bearings and bushings. Thermoplastic bushings were chosen for comparison instead of thermoplastic bearings because their solid design resists contamination and seizing from debris. Though contamination was not tested in this study, it was recognized as an advantage that bushings may have over bushings. This advantage needs to be validated further through dust testing and comparison to thermoplastic bearings. Testing of these thermoplastic bushings on multiple different caster models is also necessary to validate their full applicability in all settings and for all users. Following this, use of these bushings in the community through a clinical study could be conducted to get a sense of real-world performance.

3.7 CONCLUSIONS

Wheelchair caster bearing failures are commonplace in adverse environments. The ISO 7176-32 caster testing protocol has been instrumental in informing design improvements and guidelines for wheelchair casters. This comparative testing study utilized the testing protocol for comparative testing of caster bearings and bushings. The results suggest that thermoplastic bushings could serve as a durable, corrosion-resistant, and cost-effective alternative to bearings. Developing additional evidence to inform selection of wheelchair rolling components based on the application of use will aid in further reducing bearing failures and wheelchair breakdowns in the community through design and quality improvements.

4.0 CONCLUSION

Wheelchair caster failures put wheelchair users at risk for multiple consequences, leading to decreased self-perceived health and quality of life. Users who use wheelchair products that provide complex rehabilitation care and greater seating, and positioning support were found to experience a greater number of high-risk caster failures. Improvements in the quality of wheelchair products are needed to mitigate the risk of failures and consequences suffered by wheelchair users.

Additional testing methods are necessary to expose these casters to the environmental factors they often experience. ISO 7176-32 provides this missing piece with corrosion, shock, and abrasion exposure testing. Calibrating the failure modes and time-to-failure of this testing method to community evidence is a vital step in adding further validity to this protocol, and this work has established an initial baseline relationship of these values.

Wheelchair caster bearing failures are commonplace in adverse environments. The ISO 7176-32 caster testing protocol has been instrumental in informing design improvements and guidelines for wheelchair casters. Results of the rolling element comparative study suggest that thermoplastic bushings could serve as a durable, corrosion-resistant, and cost-effective alternative to bearings. Developing additional evidence to inform selection of wheelchair rolling components based on the application of use will aid in further reducing bearing failures and wheelchair failures in the community.

Overall, large data sets of failure information gathered from the community can be instrumental in identifying trends in wheelchair quality and performance. This in turn can inform part design and testing protocols, raising the quality of wheelchair products.

4.1 FUTURE WORK

Comparing the testing results to failure findings reported in this work and communicating design changes to manufacturers is necessary to improve quality and design. Additionally, as the WRR data grows and more failure timepoints and purchase dates become available, it will be possible to more reliably compute time-to-failure for multiple models and wheelchair parts and inform the frequency of preventative maintenance events. Once this is more accurately known, studies that utilize preventative maintenance practices can be conducted to see the effect it has on the lifetime of the wheelchair and the quality of life of the user.

Large datasets, while useful, lose the information regarding how and why something is failing the way it is. The use case of tilt-in-space wheelchairs must be studied as it is most likely vastly different from its ultralightweight counterpart which is leading to a different failure mode. Now that a baseline relationship has been established between the time-to-failure of community and laboratory casters, the next steps should consist of experimentation to eliminate any significant differences between these two sets of values. Full wheelchairs should be acquired if the corresponding caster models had differences between these two results to understand their performance. This will allow the authors to develop more accurate procedures for caster testing.

These community data findings can also be utilized to train and educate users, manufacturers, suppliers, clinicians, and policy makers on the state of wheelchair quality, performance, and best practice. For instance, users can be given bearings and taught how to replace them on their own to increase independence and function. Users should participate in maintenance training programs and educate themselves on using validated maintenance tools (Toro Hernandez, 2016) to mitigate the risk of breakdowns and consequences. Service repairs by technicians are associated with a significant reduction in high-risk caster failures (Mhatre et al., 2021). Some service repairs may not be performed owing to the complexity and the lack of tools and capabilities. In such cases, providers shall be incentivized by insurance for conducting the repairs in collaboration with users and caregivers, perhaps remotely using telehealth approaches. Policy makers can work to ensure that manufacturers must have their products independently tested and the results publicly shared.

Results from the bearing and bushing comparative study suggest that bushings may be a more durable and cost-effective alternative to roller bearings, and therefore reduce the incidence of bearing failure in the community. However, there is additional work required to reinforce these findings. Along with rolling resistance tests, there are additional environmental conditions that must be examined to fully evaluate bearing and bushing performance as well. Tests for dirt and dust contamination are potential additions to the testing protocol that would help to evaluate the efficiency of bearings and bushings. Following this, use of these bushings in the community and on various caster models through a clinical study could be conducted to get a sense of real-world performance.

Overall, this work creates a blueprint for the analysis and application of large community datasets on the failure and improvement of wheelchair components. It should be followed in a similar manner to measure and improve the quality of batteries, backrest, armrest, footplate, frame, brake, and other wheelchair components. Utilizing community data this way forms a cycle that continuously informs wheelchair testing standards and leads to design improvements, proper component selection, and more efficient maintenance and repair practices.

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Bibliography

ASTM International, "ASTM B117," 2016.

Borg, J. and Khasnabis, C., "Guidelines on the provision of manual wheelchairs in less-resourced settings," World Health Organization, 2008.

Centers for Medicare & Medicaid Services. DMEPOS Competitive Bidding - Home | CMS [Internet]. 2019. https://www.cms.gov/Medicare/Medicare-Fee-for-ServicePayment/DMEPOSCompetitiveBid/index

Centers for Medicare & Medicaid Services. Details for title: 2020|CMS. 2020. https://www.cms.gov/Medicare/Coding/HCPCSReleaseCodeSets/Alpha-NumericHCPCS-Items/2020-Alpha-Numeric-HCPCS-File

Chen W. Y., Jang Y., Wang J. D., Huang W. N., Chang C. C., Mao H. F., et al. Wheelchair related accidents: relationship with wheelchair-using behavior in active community wheelchair users. Arch Phys Med Rehabil [Internet] 2011;92:892–8. https://doi.org/10.1016/j.apmr.2011.01.008.

Fitzgerald S. G., Collins D. M., Cooper R. A., Tolerico M., Kelleher A., Hunt P., et al. Issues in maintenance and repairs of wheelchairs: a pilot study. J Rehabil Res Dev 2005;42(Jan):853–62.

Fitzgerald S. G., Cooper R. A., Boninger M. L., et al. Comparison of fatigue life for 3 types of manual wheelchairs. Arch Phys Med Rehabil. 2001; 82:1484–1488

Gaal, R. P., Rebholtz, N., Hotchkiss, R. D., and Pfaelzer, P. F., "Wheelchair rider injuries: causes and consequences for wheelchair design and selection.," *J. Rehabil. Res. Dev.*, vol. 34, no. 1, pp. 58–71, Jan. 1997.

Gebrosky B., Pearlman J., Cooper R., Comparison of High-Strength Aluminum Ultralight Wheelchairs Using ANSI/RESNA Testing Standards. Top Spinal Cord Inj Rehabil. 2018 Winter;24(1):63-77. doi: 10.1310/sci16-00057. Epub 2017 Nov 20. PMID: 29434462; PMCID: PMC5791926.

Gebrosky, B., Pearlman, J., Cooper, R. A., Cooper, R., & Kelleher, A. (2013). Evaluation of lightweight wheelchairs using ANSI/RESNA testing standards. *Journal of rehabilitation research and development*, *50*(10), 1373–1389. https://doi.org/10.1682/JRRD.2012.08.0155

Hansen R., Tresse S., Gunnarsson R. K., Fewer accidents and better maintenance with active wheelchair check-ups: a randomized controlled clinical trial. Clin Rehabilitation 2004;18:631–9.

Henderson G. V., Boninger M. L., Dicianno B. E., Worobey L. A., Type and frequency of wheelchair repairs and resulting adverse consequences among veteran wheelchair users. Disabil Rehabil Assist Technol. 2020 Aug 7:1-7. doi: 10.1080/17483107.2020.1785559. Epub ahead of print. PMID: 32762567.

Hogaboom, N. S., Worobey, L. A., Houlihan, B. V., Heinemann, A. W., and Boninger, M. L., "Wheelchair breakdowns are associated with pain, pressure injuries, rehospitalization, and self-perceived health in full-time wheelchair users with spinal cord injury," *Arch. Phys. Med. Rehabil.*, 2018.

International Organization for Standardization, "ISO 492:2014 Rolling bearings — Radial bearings — Geometrical product specifications (GPS) and tolerance values" 2014. [Online]. Available: https://www. https://www.iso.org/standard/60356.html

International Organization of Standarization. (2014). ISO 7176-8:2014 Wheelchairs — Part 8: Requirements and test methods for static, impact, and fatigue strengths. https://www.iso.org/obp/ui/#iso:std:iso:7176:-8:ed-2:v2:en

International Organization for Standardization. ISO/DIS 7176-32 - Wheelchair— Part 32: Standard Practice for Wheelchair Castor Durability Testing. 2021. https://www.iso.org/standard/77566.html

James A., Igede P., Mhatre A., Brienza D., Pearlman J., Karg P., et al. Development of a Wheelchair Repair Registry. Arch Phys Med Rehabil. 2021; https://doi.org/10.1016/j.apmr.2021.02.023

Kim, J., Mulholland, S. J., "Seating/wheelchair technology in the developing world: need for a closer look," *Technology and Disability*, vol. 11, no. 1,2. IOS Press, pp. 21–27, Jan-1999.

MacPhee A. H., Kirby R. L., Coolen A. L., Smith C., MacLeod D. A., Dupuis D. J., Wheelchair skills training program: a randomized clinical trial of wheelchair users undergoing initial rehabilitation. Arch Phys Med Rehabil. 2004;85:41–50.

Mair, C., "Applied internet-of things technology in the management of wheelchair maintenance at NHS WestMARC: A retrospective," in *European Seating Symposium*, 2018.

McClure L. A., Boninger M. L., Oyster M. L., Williams S., Houlihan B., Lieberman J. A., et al. Wheelchair repairs, breakdown, and adverse consequences for people with traumatic spinal cord injury. Arch Phys Med Rehabil [Internet]. 2009 Dec [cited 2015 Jun 14];90(12):2034–8. Available from: http://www.sciencedirect.com/science/article/pii/S0003999309007151

Medicare Interactive. DME repairs and maintenance - Medicare Interactive [Internet]. 2020. https://www.medicareinteractive.org/get-answers/medicarecovered-services/durable-medical-equipment-dme/dme-repairs-andmaintenance

A. Mhatre, "Development and validation of a wheelchair caster testing protocol," Dissertation, University of Pittsburgh. 2018.

Mhatre A., Martin D., McCambridge M., Reese N., Sullivan M., Schoendorfer D., et al. Developing product quality standards for wheelchairs used in less-resourced environments. African J Disabil. 2017 Jan;6(0):15 pages.

Mhatre A., Ott J., Pearlman J., Development of wheelchair caster testing equipment and preliminary testing of caster models. *Afr J Disabil*. 2017;6:358. Published 2017 Sep 28. doi:10.4102/ajod.v6i0.358

Mhatre, A., Pearlman, J., Schmeler, M., Krider, B., Fried., J., Community-based wheelchair caster failures call for improvements in quality and increased frequency of preventative maintenance. Spinal Cord 60, 58–62 (2022). https://doi.org/10.1038/s41393-021-00689-3

Mhatre, A., Reese, N., and Pearlman, J., "Design and evaluation of a laboratory-based wheelchair castor testing protocol using community data," *PLoS One*, vol. 15, no. 1, p. e0226621, Jan. 2020.

The Pandofit Solution. ProsFit. (n.d.). Retrieved September 16, 2021, from https://prosfit.com/solution.

Pearlman, J. *et al.*, "Lower-limb prostheses and wheelchairs in low-income countries.," *IEEE Eng. Med. Biol. Mag.*, vol. 27, no. 2, pp. 12–22, Jan. 2008.

Rispin, K., Riseling, K., and Wee, J., "A longitudinal study assessing the maintenance condition of cadres of four types of wheelchairs provided in low-resource areas.," *Disabil. Rehabil. Assist. Technol.*, vol. 13, no. 2, pp. 146–156, Feb. 2018.

Schweitzer, P. A., (2010). 5.4 Thermoplasts (Thermoplastic Polymers). In *Fundamentals of corrosion: Mechanisms, causes, and preventive methods* (p. 166). essay, CRC Press.

Toro Hernandez M. L., Development, Implementation, and Dissemination of a Wheelchair Maintenance Training Program. University of Pittsburgh. 2016

Toro M. L., Bird E., Oyster M., Worobey L., Lain M., Bucior S., et al. Development of a wheelchair maintenance training programme and questionnaire for clinicians and wheelchair users. Disabil Rehabil Assist Technol. 2017;12:843–51

Toro, M., Worobey, L., Boninger, M. L., Cooper, R. A., and Pearlman, J., "Type and Frequency of Reported Wheelchair Repairs and Related Adverse Consequences Among People with Spinal Cord Injury," *Arch. Phys. Med. Rehabil.*, vol. 97, no. 10, pp. 1753–1760, Oct. 2016.

Tukey Method. In: Dubitzky W., Wolkenhauer O., Cho KH., Yokota H. (eds) 2013. Encyclopedia of Systems Biology. Springer, New York, NY. https://doi.org/10.1007/978-1-4419-9863-7_101575

Veterans' Health Administration. Veterans' Health Administration Audit of the Timeliness of VISN 7 Power Wheelchair and Scooter Repairs [Internet]. 2018. www.va.gov/oig/hotline

Wang H., Liu H. Y., Pearlman J., Cooper R. R. A., Jefferds A., Connor S., et al. Relationship between wheelchair durability and wheelchair type and years of test. Disabil Rehabil Assist Technol. 2010 Jan;5(5):318–22.

Wilson-Jene H., Mhatre A., Ott J., Krider B., Smith C., Terhorst L., Pearlman J., Rolling resistance of casters increases significantly after two years of simulated use. J Rehabil Assist Technol Eng. 2021 Aug 5;8:20556683211025149. doi: 10.1177/20556683211025149. PMID: 34408905; PMCID: PMC8365014.

World Health Organization, "Assistive technology," 2018. [Online]. Available: https://www.who.int/news-room/fact-sheets/detail/assistive-technology.

Worobey L., Oyster M., Nemunaitis G., Cooper R., and Boninger M. L., Increases in wheelchair breakdowns, repairs, and adverse consequences for people with traumatic spinal cord injury. Am J Phys Med Rehabil [Internet]. 2012 Jun [cited 2015 Jul 28];91(6):463–9. Available from: http://www.ncbi.nlm.nih.gov/pubmed/22549473