DEVELOPMENT AND VALIDATION OF A WHEELCHAIR CASTER TESTING PROTOCOL

by

Anand Ashok Mhatre

Bachelor of Engineering, University of Mumbai, India, 2007

Master of Integrated Manufacturing Systems Engineering, North Carolina State University, 2011

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This dissertation was presented

by

Anand Ashok Mhatre

It was defended on

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and approved by

Rory Cooper, PhD, Distinguished Professor in the Department of Rehabilitation Science and Technology

Mark Schmeler, PhD, Assistant Professor in the Department of Rehabilitation Science and Technology

Mark Sullivan, BSE, Advisory Board Member, International Society of Wheelchair Professionals

Dissertation Advisor: Jonathan Pearlman, PhD, Associate Professor in the Department of Rehabilitation Science and Technology

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Anand Ashok Mhatre, PhD

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The majority of wheelchairs delivered in less-resourced settings fail prematurely. This issue has been recognized by the WHO Guidelines that recommend product testing based on field conditions to evaluate and improve wheelchair quality.

This work is motivated from WHO's recommendation and this is first scientific study investigating inclusion of environmental conditions in wheelchair testing. The goals of this work were to develop a testing protocol for wheelchair casters based on field conditions, evaluate the impact of environmental testing factors on quality and make appropriate recommendations for wheelchair testing based on study outcomes.

In this study, an evidence-based approach was followed in which wheelchair testing evidence, expert advice, and field evidence were continually triangulated to inform the testing protocol development. A literature review (Chapter 1) was carried out and expert advice was sought to generate a list of testing methods with environmental factors based on outdoor failures. Caster system failure was identified as a key testing gap that poses significant safety risks to the wheelchair users. Development of a caster testing equipment (Chapter 2) and a caster failure checklist (Chapter 3) was carried out through an iterative design and review approach. The checklist was distributed for collecting failure data following psychometric evaluation and revisions. Testing factors of shock, corrosion and abrasion were validated to respective field exposures and caster testing was conducted (Chapter 4). Environmental factors impacted the durability of 25% caster models and altered failure modes for 75% models. Two-thirds of the

altered failure modes have significant risk of causing injuries to users and wheelchair failures. About 73% of the testing failures matched with the most common failure modes experienced in the field.

Based on study findings, environmental factors strongly influence both the time-to-failure and failure mode for caster models. We recommend that environmental exposure need to be considered as part of wheelchair testing protocols to help improve the external validity of the testing, which will ultimately improve the safety and reliability of the device. These recommendations are discussed along with caster design recommendations and suggestions for future work in Chapter 5.

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PREFACE

I started this PhD in the Fall of 2013 with the intention of using my skills to contribute to the field of assistive technology. So far, this journey has been more than just rewarding; it has helped me grow significantly on personal and professional fronts. Over the course, I have learnt to use some scientific methods to solve real-world problems. This dissertation work would not have been possible without the generous support of many people.

I'm pleased to be one of Dr. Pearlman's students. I'm thankful to him for investing his time in training me and for his direction and support on the projects we have worked on together. I have cherished working with him. Dr. Cooper has been an inspiration throughout. I'm grateful for his advice and allowing me to use the machine shop facilities when we were building the caster test. Further, I'm grateful for the encouragement and guidance from my other doctoral committee members – Dr. Schmeler and Mark Sullivan. I hope the caster testing standard work completed as a part of this dissertation is valuable to the wheelchair sector and can help the development of further standards.

I really appreciate the assistance and direction provided by the ISWP Standards Working Group experts while designing the caster test. I would like to thank Norman Reese, Matt McCambridge, Daniel Martin and Chris Rushman for their valuable inputs on the design. Norman Reese and Karen Rispin from Letourneau University provided field data for this study which made this dissertation a possibility. I'm deeply indebted to them for this. This study

required a lot of casters for testing which were donated by Eric Wunderlich (LDS Charities), Don Schoendorfer (Free Wheelchair Mission), Mark Sullivan (Convaid Systems), Keoke King (UCP Wheels for Humanity), Mark Richard (Hope Haven International) and Dave Mahilo (formerly at Invacare). I greatly appreciate their valuable help. I appreciate the help from Colin Mair (NHS, Scotland) on the caster failure checklist development. I would also like to extend my thanks to the participants in the checklist study for their time and volunteering.

I'm fortunate to have had a chance to work with excellent co-ops and interns. I'm thankful to Joe Ott for helping me design and build the caster test, Sam Waters and Erin Higgins for developing the ISWP product list, Stephanie Lachell for her assistance with the checklist and testing studies, and Stephanie Vasquez and Mauricio Arredondo for translating the checklist. I appreciate the support given by Nancy Augustine, Kim Robinson, Krithika Kandavel, Michael Lain, Ron Wesolowski, Patricia Karg and Joe Ruffing during this PhD. I'm grateful to the folks in the machine shop – Garrett Grindle, Mark McCartney, Ben Gebrosky and Josh Brown for their help and advice on my projects.

The most important appreciation goes to my family, friends and roommates (who are now lifelong friends). I would not have finished this PhD without their unconditional support, love and care. I owe a debt of gratitude to my brother for being there with my parents while I have been away. Lastly, I would like to dedicate this work to my grandparents. They have been instrumental in raising me and I have no words to express how much they have been missed. I hope to seek their strength and wisdom as I look forward to graduating and beginning a new phase in my life.

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Nomenclature:

HWC: Hospital style wheelchair

ISO: International Organization for Standardization

ISWP: International Society of Wheelchair Professionals

ISWP-SWG: International Society of Wheelchair Professionals' Standards Working Group

LRS: Less-resourced settings

LWC: Lightweight wheelchair

MWC: Manual wheelchair

RS: Resourced settings

UN: United Nations

UN-CRPD: United Nations Convention on the Rights of Persons with Disabilities

USAID: United States Agency for International Development

UWC: Ultra-lightweight wheelchair

WHO: World Health Organization

WHO Guidelines: WHO Guidelines on provision of manual wheelchairs in less-resourced settings

1.0 INTRODUCTION[1]

A wheelchair is one of the most commonly used assistive devices for enhancing personal mobility, which is a precondition for enjoying human rights and living in dignity and assists people with disabilities to become more productive members of their communities [1].

There remains a vast need for quality wheelchairs around the world and there are a couple of reasons why this need is bound to increase with time. First, global ageing is increasing at a significant rate and life expectancy has improved significantly due to advances in medicine technology. Ageing will continue to rise in the coming decades and significantly in developing parts of the world [2-5]. Second, there is a rising prevalence of injuries due to road traffic crashes, violence, falls, acts of war and natural disasters [6-8]. These two factors are responsible for causing reduced physical functioning and temporary or permanent disabilities [6, 7] which in turn, is accelerating the need for wheelchairs around the world.

There is a lack of consensus on the number of people needing wheelchairs. The World Health Organization's Guidelines on provision of manual wheelchairs in less-resourced settings

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[1] A portion of this Chapter's Introduction, Methods, Results and Discussion is published in the manuscript "Developing product quality standards for wheelchairs used in less-resourced environments" in the African Journal of Disability. By Anand Mhatre, Daniel Martin, Matt McCambridge, Norman Reese, Mark Sullivan, Don Schoendorfer, Eric Wunderlich, Chris Rushman, Dave Mahilo and Jon Pearlman.

(WHO Guidelines) published in 2008 reported that 10% of the world's population has disabilities and 10% of people with disabilities need wheelchairs which was 65 million at the time [1]. In 2011, Handicap International reported that 105 million people needed wheelchairs based on fact that people with disabilities constitute about 15% of the world's population as per the World Report on Disability [9, 10]. Later, the wheelchair service training packages developed by WHO and USAID in 2013 stated the number is 70 million with only 5-15% of that number having access to a wheelchair [10-12]. Considering 85% not having access, 15% of the world's population (about 7.5 billion) has a disability and 10% of them require wheelchairs, it can be said that the unmet need comes to around 95 million wheelchairs [13]. The need is massive in less-resourced settings (LRS) as an estimated 80% of people with disabilities live there [14].

To address this need and improve the quality of life of wheelchair users and others with disabilities, several international organizations are promoting improved accessibility to appropriate technology [1, 5, 14]. The WHO Guidelines is a key document that recognizes several issues with wheelchair provision in LRS including lack of appropriate products, regulations for product and service provision, funding, disability inclusion in policies, trained personnel and awareness [1, 15-20]. The Guidelines identify inconsistencies in wheelchair product quality as a major problem.

Wheelchair designs provided in LRS and their quality vary based on the service delivery and funding methods [17, 19, 21]. Donated, refurbished and locally produced wheelchair models are often hospital style wheelchairs or transportation chairs used in clinical settings (see Figure 1). These designs are not appropriate for outdoor use as they are based on designs for indoor and institutional use [17, 21-27]. Quality is often traded for cost savings as some designs include plastic wheels and cushions which are not durable enough, while some lack features like folding frame and essential parts such as parking brakes, push rims, resilient casters, etc. which makes the product inappropriate for use [17, 22, 26, 28, 29].

Figure 1. Hospital-style wheelchair [30].

Durability was given the highest priority among all wheelchair features by users (n=243) in one of the early studies on wheelchairs [31] but it still remains a concern in both, LRS and RS.

A recent study in the United States reported 62.6% repairs and multiple adverse consequences with manual wheelchair users (n=352) during 31 months of use [32]. About 70% users needed repairs with wheels and casters. Between the wheelchair types, power wheelchairs have suffered significantly more breakdowns than manual wheelchairs [33]. Across the 10 most prescribed power wheelchairs, 54.5% to 73.9% of users (n=378) required 1 or more repairs over a 6-month period [34]. Wheelchair designs in RS additionally have stability issues. Field evidence indicated tips and falls out of chair as the prime culprits for causing 68-80% of accidents and adverse events [33-41].

More than 75% of users (n=94) were found to be dissatisfied with the durability and weight of unsuitable products that were provided in Zimbabwe [27]. Anecdotal reports state that donated wheelchairs often last no more than three to six months [17, 18, 22]. Products are known to incur frequent breakdowns which in turn, can lead to decreased functional status and secondary health complications for the user [17, 19, 27].

In addition to poor quality, products are not contextually appropriate. Outdoor environments in LRS often include unpaved and soft surfaces, muddy roads, potholes, high curbs, gravel, sand, water, steep inclines and inaccessible buildings and public spaces [1, 18, 22, 23, 26, 42-44]. Maneuvering over rocky surfaces and obstacles exposes wheelchairs to heavy shocks and persistent vibrations. Varying seasonal conditions, elevated temperatures and high humidity fosters increased corrosion, ageing and wear. Such unique conditions place additional requirements on wheelchair durability which can cause premature failures if the product quality is poor [1, 16, 18, 25]. Failures in the community because of product-environment mismatch can cause adverse consequences such as accidents such as tipping or falling out of wheelchair [1, 19, 20, 43, 45-47]. Missing school or work, loss of income and reduced social participation are other consequences along with chances of user's health complications due to wheelchair breakdown.

User behaviours are also different in LRS compared to those in resourced settings (RS), which should be considered during wheelchair design [1, 16, 23, 48]. For instance, wheelchairs must withstand the stresses caused by rough handling, as they are tossed on and off the roof of a bus. Furthermore, they need to be light and compact enough to be agile and easily portable [42]. Additionally, users often leave their wheelchairs outside exposed to the weather, or use them as shower chairs [1, 49]. Users also frequently transport goods on the push handles, seats, footrests or other parts of the wheelchair as well as carry passengers on armrests or footrests. Thus, the diverse functional requirements for wheelchairs impose greater durability requirement on the designs [1].

Along with poor quality and adverse environmental and use conditions, lack of regular maintenance, repair and access to rehabilitation services makes wheelchairs unreliable for use [1, 50]. Regular maintenance is necessary for reducing breakdowns, part failures, occurrence of adverse events (e.g. accidents) and improving reliability [46, 47, 51, 52]. WHO guidelines recommend conducting user training in regular maintenance and basic wheelchair repair by the wheelchair service personnel. However, lack of wheelchair service professionals and limited awareness of best service delivery practices make user training difficult.

Unavailability of resources including materials, spare parts, tools, equipment, workshop facilities and skilled technical labour create challenges for repair [1, 17-20, 28, 53]. If an imported or donated wheelchair breaks down, it is difficult to find replacement parts and expensive to buy or import them [18, 22, 43]. As a result, breakdowns are not quickly addressed [15, 49]. If not addressed, breakdowns can make loss of mobility long term because users in LRS do not have backup wheelchairs [42]. This, in turn, has multidimensional consequences for the user, including reduced satisfaction and increased likelihood of device abandonment [36, 54].

1.1 GLOBAL EFFORTS TO IMPROVE WHEELCHAIR QUALITY

The international wheelchair community recognizes the problem with wheelchair quality deficiency in LRS and several international humanitarian and charitable organizations are promoting access to high-quality, appropriate products. For example, the United Nations Convention on the Rights of Persons with Disabilities (UN-CRPD), which has been ratified by 156 countries, specifically mentions the importance of assistive technologies (ATs) in eight of its Articles (4, 9, 20, 21, 24, 26, 29 and 32) [14]. Article 20 of the UN-CRPD which focusses on personal mobility indicates that state parties must facilitate personal mobility for people with disabilities that is affordable, high quality and includes relevant training. To accelerate the implementation of UN-CRPD initiatives, the UN partnered with WHO in 2013 and initiated a programme called the Global Cooperation on Assistive Technology (GATE) [55]. As a part of this programme, WHO recently published a Priority Assistive Products List (APL) which among other includes both manual and attendant-propelled wheelchairs with and without postural support options [56]. Table A 1 shows the wheelchair types promoted by the GATE APL.

In 2006, wheelchair quality issues were discussed in a consensus conference held by several experts and stakeholders involved in wheelchair provision [18]. The outcome of this conference was the development of WHO guidelines for provision of manual wheelchairs in LRS that encourage development of high-quality, appropriate wheelchairs. WHO has also developed wheelchair service training packages in partnership with the United States Agency for International Development (USAID) [1, 11, 12]. The International Society of Wheelchair Professionals (ISWP) was formed in 2015 with a seed grant from USAID to the University of Pittsburgh [57]. ISWP’s mission is to professionalise the wheelchair sector by promoting standardization of wheelchair services, coordinating wheelchair activities and raising awareness of the need for proper wheelchair services around the world. ISWP’s initiatives are carried out through working groups. ISWP’s Standards Working Group (ISWP-SWG) focusses on improving wheelchair product quality. This group is composed of wheelchair manufacturers, designers, providers from charitable organisations and field experts with work experiences in LRS. Table A 2 lists the members of ISWP-SWG. Initiatives of this group are led by the directions by the WHO Guidelines on product quality improvement.

The first recommendation by the WHO Guidelines is testing wheelchairs delivered in LRS prior to distribution. The guidelines advocated using international wheelchair testing standards published by ISO as a basis to develop and adopt national standards in LRS. The second recommendation is to develop additional quality testing standards considering the environmental, user and resource conditions experienced in LRS.[1] With WHO recommendations in mind, a literature review was undertaken and expert advice from ISWP Standards Working Group members was sought to identify exactly which additional tests need to be developed.

1.2 IDENTIFYING ADDITIONAL TESTS

A literature review of wheelchair standards development, wheelchair standards testing studies and wheelchair field evaluations in LRS was carried out in early 2015.

1.2.1 Methods

1.2.1.1 Methods – Literature Review

The literature search was conducted on scientific and medical databases from the earliest time permitted electronically using PubMed, CIRRIE, EBSCO Host and Scopus. Keywords used for searching titles (and title or abstract for PubMed) in alphabetical order were: wheelchair + ANSI/RESNA, assessment, comparison, environment, evaluation, ISO, performance, review, standards and testing. There was no limitation placed on the year of publication. Duplicates were removed, and titles of the selected articles were screened by the author and assisting researcher and saved for further screening. Articles were then retrieved using the University of Pittsburgh library. Further review of articles based on abstracts was carried out by the author and the researcher. If an article was deemed relevant to the topics of interest by only one reviewer as per the abstract, then both reviewers read through the article to determine its relevance. Studies on motorised wheelchairs, scooters and manual suspension wheelchairs were not taken into account as the available wheelchairs used in LRS are mostly manual [28]. The papers that were deemed relevant were read entirely and reviewed by the author and other researcher for inclusion in this literature review. References found from screened articles were searched using PubMed and Google Scholar or physically retrieved. Included articles were categorised into the four categories: (1) ISO standards development, (2) wheelchair testing with ISO standards and (3) studies reporting wheelchair failures in LRS.

Data collection and analysis was performed by the primary author. The articles related to ISO standards were evaluated for understanding whether environmental and use conditions were considered during the test method development process. Extracted elements from studies on ISO wheelchair testing included wheelchair sample size, ISO durability testing results and part failures. For articles related to wheelchair use in less-resourced communities, information was retrieved on study design, wheelchair ISO qualification, maintenance status and field failures.

1.2.1.2 Methods – Expert Advice

Advice on additional test development was sought from nine members of the ISWP Standards Working Group (ISWP-SWG). This expert group is composed of wheelchair manufacturers, designers, providers from charitable organisations and field experts with work experiences in LRS. All experts were familiar with ISO 7176 test methods. Information on failures in LRS and test development was collected through biweekly group discussions through Web conferencing via Adobe Connect [58]. ISWP-SWG members provided pictures of broken and inoperable parts that they had collected through their work to demonstrate the types of failures common in LRS. Group discussions were centred around these failures that are not predicted by ISO 7176 tests. The failure photos were instrumental in gaining consensus about the common failures and making suggestions for the additional tests needed. Votes were taken within the group to nominate parts for testing consideration.

A systematic process was used to generate a prioritized list of the new tests recommended from this work. First, a product testing matrix was generated that includes a column listing the failures common in LRS that were identified through the literature review and by the members of the ISWP-SWG. Test conditions responsible for failures were noted. Second, experts determined whether the test conditions are already included in ISO 7176. Third, if a need for additional testing was identified, an effort was made to leverage existing test methods from relevant ISO standards, American Society for Testing and Materials (ASTM) standards and United States Military Standards (MIL-SPEC). If it was determined that a suitable test method did not already exist, members from the ISWP-SWG made suggestions for new test methods. Voting was carried out in the group to select test methods to be developed by ISWP.

1.2.2 Results

The flow chart outlining the selection process of articles is shown in Figure 2. Of the 1112 citations retrieved and 15 citations found through references of screened articles, 35 articles met the inclusion criteria and were categorised and analysed further. A reference book titled "Wheelchair Selection and Configuration" [59] and ISO 7176 Standards Documentation [60] was included in this review as well.

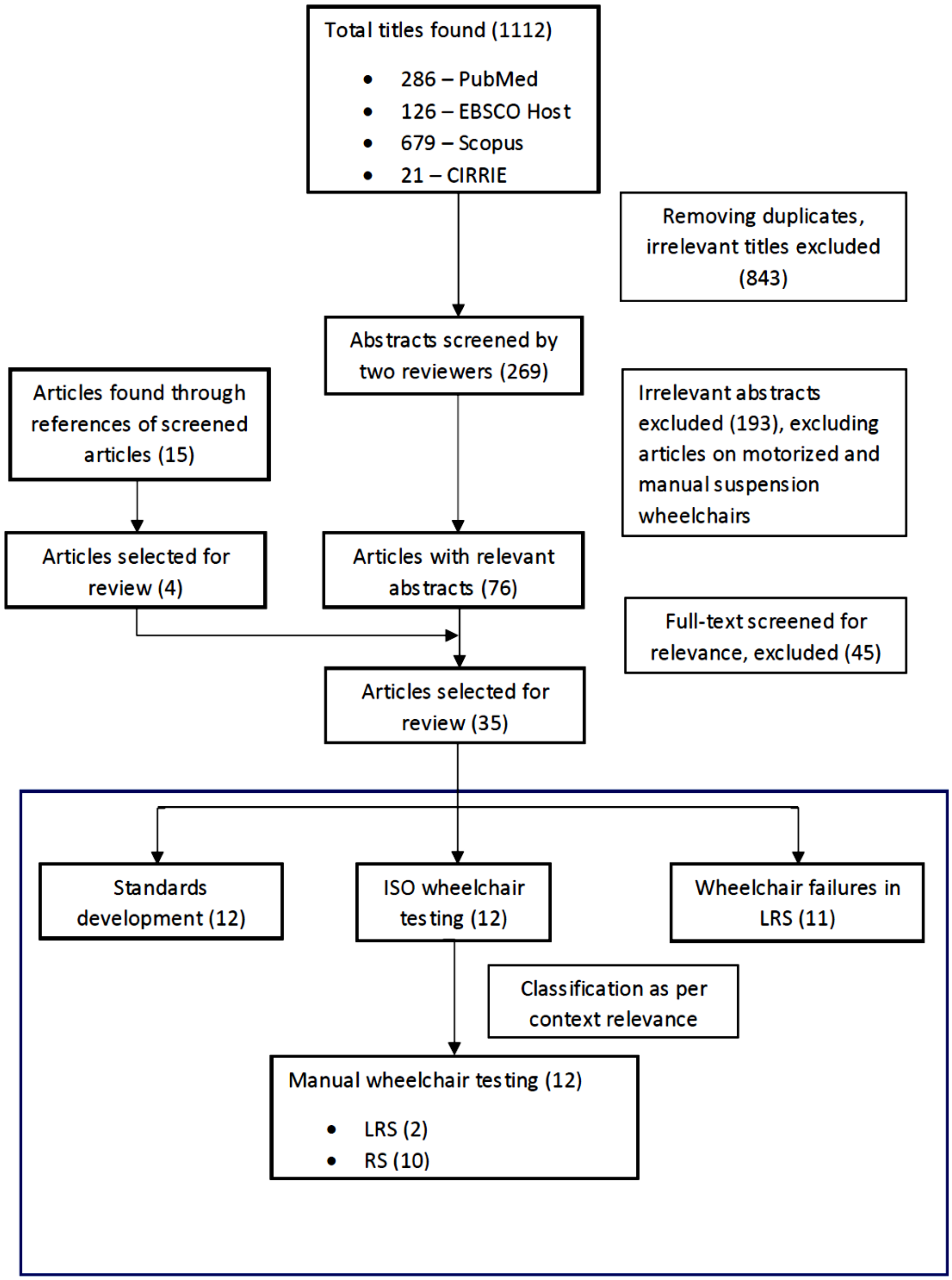

Figure 2. Flowchart of article selection process for review.

1.2.2.1 Wheelchair Standards Development

Wheelchair standards development began in the 1960's in United States (US) with others including Canada, Germany, Scandinavia, Great Britain, and Japan testing wheelchairs on their own for years [61]. Staros et al. reports publishing of standards for "push" wheelchairs by the Veterans Administration Rehabilitation Engineering Centre (VAREC) in 1977. Three lightweight wheelchairs, a push-rod propulsion wheelchair, a lever-drive chair and standing wheelchair were tested by VAREC at various Veteran Administration (VA) centres using these standards. Durability and stability tests included in the VAREC Standards are similar to the ones adopted by the International Standards Organization (ISO) [61]. Powered WC standards were published by VA in 1981. The main purpose of developing these VA standards was qualifying wheelchairs purchased from suppliers [62]. In Europe, wheelchair acceptance standards existed in Germany and Sweden as well with some countries having their own testing agencies [63]. Differences in testing standards across the European countries resulted in varying product quality and stifling trade [64].

The ISO work on WC standards commenced in the early 1980's with participation from UK, Sweden, Germany, France, Denmark, US, Canada, Austria and Japan [63, 65]. On the ISO technical committee, United States was represented by American National Standards Institute's Technical Advisory Group (ANSI TAG), organized by the Rehabilitation Engineering Society of North America (RESNA) [66]. The ISO and ANSI/RESNA committees included a diverse group including engineers, clinicians, manufacturers, consumer representatives and representatives from regulatory agencies [63]. Funding for such standards work was provided by the VA, the Paralyzed Veterans of America (PVA) and wheelchair manufacturers [62]. For Europe, the European Committee for Standardization (CEN) Technical Committee TC173 were involved in

ISO work. CEN standards included manual wheelchair standards (EN12183) and power wheelchair standards (EN12184) with some additional requirements and test methods that were in development for Europe specifically [64].

In the 90's, about 23 standards were under development and the ISO committee published some standards related to safety, durability, maneuverability, and transport of manual and powered wheelchairs, including scooters [65, 67]. In his book "WC Selection and Configuration", Cooper et al. outlines the organization of Sub Committee (SC1) and working groups responsible for standards under the ISO Technical Committee 173. Development of standards is a lengthy process; test procedures need to be validated among laboratories and among various wheelchairs and, should be approved by 75% of participating nations. The development and validation process is iterative which results in refinement of test procedures and eventually, standards get voted on several times before approval. All ISO standards are reviewed every five years and revisions are made as deemed necessary [65, 67].

Currently, there are 24 countries participating in the ISO SC1 committee (11 observing countries) including Brazil, China, and India that are considered les-resourced countries. There are now 34 standards published by the committee with expanded categories that include power wheelchairs, scooters and stair-climbing devices. Standards specify disclosure requirements for testing and methods of measurement for: static stability (§1), dynamic stability (§2), brake effectiveness (§3), energy consumption (§4), wheelchair and seat dimensions (§5), maximum speed, acceleration and deceleration (§6), determination of seating and wheel dimensions (§7), static, impact and fatigue strength testing (§8), climatic testing (§9), obstacle climbing ability (§10), test dummy specifications (§11), power and control system (§14), flammability requirements (§16), electromagnetic compatibility (§21), setup procedures (§22) and vocabulary

(§26). In all, wheelchair standards tests consist of durability, safety and performance tests along with measurement and reporting of wheelchair dimensions and characteristics. Some test procedures allow for comparison between wheelchair safety and performance, while certain tests need the wheelchair to pass minimum requirements [60, 65, 67].

Durability tests are the soul of WC standards tests in which the entire wheelchair is subjected to severe mechanical strains and stresses. The ISO 7176-8 suite of tests includes tests for strength, impact and fatigue which primarily assess a wheelchair's robustness. Strength tests require static loading of armrests, footrests, handgrips, push handles and tipping levers. Impact tests are conducted with a 10-kg test pendulum on backrests, hand rims, footrests and casters. Fatigue tests consist of a multi-drum test (MDT) of 200,000 cycles and a curb-drop test (CDT) of 6,666 cycles (see Figure 3). Failures of the MDT and CDT are classified into three classes: Class I and Class II failures are because of maintenance issues and can be fixed by a user or dealer, while Class III failures are caused by structural damage and require a major repair or part replacement A Class III failure indicates failure of the test [59, 60].

The ISO 7176 series includes wheelchair standards that are intended to apply universally to all contexts, and many national standards committees have adopted ISO 7176 [1]. In United States, the ANSI/RESNA standards are mostly consistent with ISO 7176 [68, 69]. The ISO 7176 has been adopted in many countries including Canada, Great Britain, South Africa, China, Japan, Australia and New Zealand as well.

1.2.2.2 ISO Wheelchair Testing Studies

The literature review on wheelchair testing with ISO standards focused on 12 articles [69-80] that deal with laboratory testing of different wheelchair designs. Included were HWCs, lightweight wheelchairs (LWC) and ultra-lightweight wheelchairs (UWC) (see Figure 4). Wheelchair models were in new condition and were already available on the market. Information regarding their prior ISO testing was not available. Some testing studies referred to ANSI/RESNA standards. Table 1 presents study results from ISO section 8 fatigue tests and lists the observed failures.

Figure 3. Lightweight wheelchair (left) and Ultra-lightweight wheelchair (right)[81]

Among different designs, UWCs were found to be more durable and cost-effective compared to LWCs and HWCs except in the most recent study [76]. UWCs experienced higher Class I failures that could be repaired by users, whereas HWCs had greater Class III failures [73].

Table 1. Findings from the International Organization for Standardization standard testing studies of manual wheelchairs (MWCs).

Samples	Test results and critical failures
ISO Testing of manual wheelchairs (no data available on design type and manufacturers)	
9 MWCs	All wheelchairs failed on MDT. Failures observed with caster spindle, bearings and alignment. Bent cross braces were found. Splaying and toe-outs observed in rear wheels [72].
46 MWCs	Twenty-seven of 46 wheelchairs failed the MDT and CDT tests. Twenty-eight of 38 wheelchairs tested until failure incurred frame failures [77].
154 MWCs	Seventy-five of 154 wheelchairs failed the MDT and CDT tests. No evidence on type of failures was included [78].
ISO Testing of wheelchairs produced and used in LRS	
2 HWC models	Both wheelchairs failed MDT. Failures noted were wheel coming off axle, flat pneumatic insert and tire, right hub failure, caster tire wear out and caster fork crack [80].
One HWC	Wheelchair failed on MDT. Cross-brace failure occurred [79].
ISO Testing of wheelchairs used in RS	
61 MWCs from four manufacturers: 25 HWCs, 22 UWCs and 14 LWCs	Eighty-three per cent of the HWCs, 61% of the LWCs and 24% of the UWCs failed MDT. Twenty-One Class I failures, 29 Class II failures and 45 Class III failures were noted. Caster assembly and frame failures were found [73].
6 HWCs and 9 UWCs	All HWCs failed the MDT. One of nine UWCs failed on CDT. Failures with footrest weld, caster spindles, side frame, cross braces and caster spokes were reported [71].
Three samples of three LWC models	Eight of nine LWCs failed MDT and CDT tests. Several side frame failures occurred in weld areas, one caster spindle failure and one cross-brace failure [70].
Three samples of three LWC models	All wheelchairs passed the strength tests. Seven of nine LWCs failed the MDT and CDT tests. Several frame failures were observed [74].
Three samples of four aluminium rigid UWC models	All wheelchairs passed impact strength tests and brake fatigue tests. Five of 12 chairs failed MDT and CDT tests [75].
Three samples of four UWC models	One of 12 UWCs failed MDT and CDT tests. Caster stem failures, weld, a rear wheel bearing, and frame failure were noted [69].
Three samples of three titanium rigid UWC models	All wheelchairs passed the strength tests. Nine of 12 UWCs failed the MDT and CDT tests. Several backrest cane failures were noted. Sliding footrests and spoke failures on rear wheels were noted [76].

1.2.2.3 Wheelchair Failure Evidence

Failures found in field studies with different wheelchair models are listed in Table 2. Five of the reviewed studies [29, 53, 82-84] evaluated usability and/or durability aspects of wheelchairs designed for LRS. These models (see Figure 4) have passed ISO durability tests and were developed by non-profit organisations [29, 49]. They are adjustable and more appropriate for rigorous use in rugged conditions [18, 19, 27, 32, 42, 85]. Despite wheelchairs passing ISO testing, breakdowns and failures occurred frequently and within months of the wheelchair being delivered [29, 30, 80, 82-84], which reinforces the recommendation from the WHO guidelines that additional tests should be developed.

Figure 4. Wheelchair models designed for less-resourced environment use [30].

Table 2. Field failures of manual wheelchairs in less-resourced environments.

Author and year	Study details	ISO testing status	Maintenance status	Field failures
Studies including HWC style designs				
Toro (2013) [80]	Cross-sectional survey study conducted in a rehabilitation facility in Mexico. Paediatric users of donated HWCs (n = 43) were included in the study. Wheelchair use = 20 ± 16 months.	Wheelchairs failed on ISO test.	Self-repair and modifications	Failures noted were flat tires and reattachment of drive wheel. This study reported extended results from an earlier study [47] reported below.
Shore and Juillerat (2012) [86]	Cross-sectional survey study conducted in Vietnam, Chile and India. Donated semi-rigid HWCs (n = 519) were included in the study. Wheelchair use = 12 months.	Not ISO tested	Self-maintenance	A minimal repair rate of 3.3% was reported. Repairs were required for wheels, brakes, footrests and harness.
Toro (2012) [47]	Cross-sectional survey study conducted in a rehabilitation facility in Mexico. Paediatric users of donated HWCs (n = 23) were included in the study. Wheelchair use = 20 ± 16 months.	Not ISO tested	Self-repair and modifications to wheelchairs	Fifteen of 23 repairs or modifications were reported. Twenty of 23 wheelchairs were in damaged condition based on clinician rating. Inoperable brakes, loose seat and back-sling upholstery, worn out casters, cracked rear wheels and damaged armrests were reported.
Shore (2008) [87]	Cross-sectional survey study conducted in Peru and India. Donated rigid HWCs (n = 188) were included in the study. Wheelchair use = 6–33 months.	Not ISO tested	Self-maintenance	Problems with flat rear tires and tire valves were reported. Minor issues with the resin chair were seen too. Twenty-eight per cent users reported repairs within past 18 months.

Table 2 (continued).

Mukherjee and Samanta (2005) [88]	Cross-sectional survey study conducted in India. Donated rigid HWCs (n = 162) were included in the study.	No data available on testing of the HWCs	No maintenance	Casters, wheel bearings, axles and solid tires were reported to be frequently damaged. Extensive repair was required with very little wheelchair use. A total of 15.17% of WCs were found to be damaged beyond repair.
Saha (1990) [89]	Cross-sectional survey study conducted in India. Locally produced HWCs (n = 50) from two manufacturers with wheelchair usage of 3–4 years.	No data available on testing of the HWCs	No maintenance	Multiple failures reported with caster bearings, fractures with spokes, footrests, caster wheels and forks. Brakes, seat and back material were found to wear rapidly. Rusted parts were observed.
Studies with wheelchair models designed for LRS				
Reese and Rispin (2015) [82]	Cross-sectional survey study conducted in Kenya with paediatric users (n = 87). Failure data collected on five wheelchair models. Wheelchair use = 12–24 months.	Four of five wheelchair designs were ISO qualified. The non-tested model was adapted from one of ISO qualified model[90].	Irregular maintenance	Brakes were found to become loose, rusty or stiff and misadjusted. High occurrence of loose, wobbly hubs, some missing hand-rims or nuts, worn tread and flat tires was noted. Casters suffered from missing bearings and tire cracking. Bent frames with rust and paint chips were observed. Armrests often showed significant degradation, breakage or loosening. Seats and seat backs showed collapsing of the foam. Their covers were cracked and torn. Common footrest problems were rotation stiffness, broken parts and obvious repairs, excessive looseness, cracked or broken foot plates, rusting and paint chips.

Table 2 (continued).

Rispin (2012) [83]	Cross-sectional study conducted in Kenya with paediatric users (n = 30). Failure data collected on two models: one model used for 2 weeks and the other one for 8 months.	The model evaluated after 2 weeks of use was adapted from one of ISO-qualified model[90]. The other model was ISO qualified.	No maintenance	The ISO-qualified model had stiff brakes and broken trays and footrests. Some waterproof vinyl covers, and cushions needed replacement. The other model had repeated flat tires and misaligned wheels within 2 weeks of use.
Studies with appropriate wheelchair provision of wheelchair models designed for LRS				
Toro (2016) [84]	Paediatric and adult wheelchair users (n = 142) were evaluated in Indonesia. Four wheelchair models were provided. Wheelchair use = 6 months.	Two of four wheelchair designs were ISO qualified	Self-maintenance	Fewer self-repairs were needed. Casters, seat, armrests, push handles and frame repairs on ISO tested models. Footrests, frame, armrests and push handles were self-repaired on other models.
Rispin (2013) [29]	Paediatric users (n = 10) in Kenya were evaluated following provision of two wheelchairs models. Wheelchairs were fit to users. Wheelchair use = 3 months.	ISO-qualified wheelchairs	No maintenance	Failures were noted with one chair only. Tires were often flat. The seat and seat back fabric was more often cracked and torn. The cushions were collapsed. Manufacturing quality control issues were found with different parts.
Armstrong (2007) [53]	Prospective usability study (n = 100) conducted in Afghanistan with one wheelchair model. Three follow-up visits at weeks 3 and 10 and after 4 months were conducted. Failures reported are during the visits. Wheelchair use = 4 months.	ISO-qualified wheelchair	Self-maintenance, repairs and replacements conducted during follow-up visits by practitioners	Brake handle design issues (×105), failure with seat fabric (×1) and rear wheel inner tubes (×6) were reported. Replacements and repairs were conducted with seat and back fabrics, brake handles, footrests, calf straps, caster wheels and rear wheel inner tubes during follow-up visits.

1.2.2.4 Expert Advice

The ISWP-SWG members reported minimal participation from countries having LRS in ISO 7176 standards development. They noted several product quality issues in LRS through failure photos shown in Table 3. The service delivery method and the status of maintenance, repairs and user skills training for wheelchairs in Table 3 are unknown. These failures and breakdowns are irrespective of location of manufacture (locally produced or imported) and the context for use (RS or LRS). ISWP-SWG members identified certain unique quality-affecting elements such as corrosion, ageing and high impact forces (e.g. if a wheelchair is dropped from a bus) as causes for these failures. These elements are not present in ISO durability tests. Rapid breakdowns of components such as upholstery, anti-tippers, belt harness, calf straps, toe straps and fasteners were noted as durability issues that are not tested under ISO 7176.

Table 3. Failures noted by International Society of Wheelchair Professionals Standards Working Group experts on wheelchairs designed for use in LRS.

Field failures	Failure photographs
Casters: Casters are damaged because of abrasion of tires and wide-ranging loads on rough and unpaved terrains, accelerated ageing of material and corrosion. Other issues are caster instability because of flutter and caster floatation (performance after penetration in soft ground).	 Casters after 15 months of ISO-tested wheelchairs
Rear wheels and tires: Tire type can have a big impact on rollability. Spokes break, tires puncture and poor air retention are evident on rocky unpaved terrain. Wheels lose shape as they deform and wear too quickly.	 Tire condition for end-of-life wheelchair

Table 3 (continued).

Bearings: Quality of bearings (seal, lubrication, the ability of a type of bearing to tolerate contamination and loss of lubrication) can have a huge impact on rollability. Bearings rust easily because of contamination – debris causes resistance in propulsion. Larger turning force required on casters.	 Corroded caster bearing from an ISO tested wheelchair after 15 months of use (left) and fractured bearing (right)
Back and seat upholstery: Sling designs may make the rider sit in a poor-seated position increasing risk of pressure sores. Upholstery is observed to sometimes tear or loose easily or hold moisture. Covers are not waterproof and chemical-resistant. Failure often occurs at mounting points.	 Upholstery issues
Back and seat cushion: Foam can retain moisture which can lead to pressure sores. Non-standard cushions compress too easily and collapse.	 Worn-out seat sling and back support
Brakes: Brakes come out of adjustment easily or fall apart because of loosening over time and corrosion. Some designs use soft malleable plastic as a bushing material which cannot endure significant loads. Some designs lose protective covers exposing protruding metal elements which may pose risk during transfers.	 Worn-out brake from an ISO-qualified wheelchair

Table 3 (continued).

Footrests: Footrests have poor strength; they often break because of contact with the ground when descending curbs or surface depressions.	 Broken footrest
Frame and cross braces: Rust because of corrosion often caused by paint chipping, poor paint application or pooling of water inside tubes. Poor strength of frame causes backrest failure, wheel misalignment, failure with push handles or canes. Bent frames are typical. Rust degrades folding mechanism.	 Frame failure on an end-of-life wheelchair
Arm pads: Worn-out arms pads are frequent.	 Worn-out arm pad after 14 months of use

1.2.2.5 Additional test methods identification

To identify new tests, a product testing matrix as shown in Table 4 was generated that lists failure modes of different parts and the applicability of ISO test methods for predicting each failure mode. Testing priority was assigned by consensus from experts based on parts that fail most often and make the wheelchair non-functional. The lack of standard test methods (ISO, ASTM and MIL-SPEC) for predicting most failure modes on wheelchair parts led ISWP-SWG to prompt that new test methods should be developed.

Table 4. Product testing matrix.

Components	Failure modes	Test factors	Priority	ISO test methods
Casters, rear wheels and bearings	Tire type, wheel and caster features and bearings affect rolling resistance	Rollability: Effort required to propel wheelchairs on paved and unpaved surfaces	High	Not in ISO 7176
	Broken caster and wheel parts	Durability: impacts and loads; fracture loads		Yes (ISO 7176-8), but does not reproduce complex load conditions that occur in LRS.
	Worn out tires	Durability: abrasion		Not in ISO 7176
	Parts degradation	Durability: accelerated ageing		Not in ISO 7176
	Corroded bearings and metallic parts	Durability: corrosion		Not in ISO 7176
	Fluttering caster may waste effort and cause accidents	caster flutter		Seen on ISO 7176-8 multi-drum test but not tested for.
	Tire puncture	Air retention for wheels, puncture tests		Not in ISO 7176
	Worn out bearings, dirt and dust in bearings	Test lubrication quality, seal design and quality		Not in ISO 7176
	Trueness of wheels over time is affected, camber issues	Wheel alignment		Not in ISO 7176
Seat cushion and upholstery	Seat cushions flatten over time.	Durability: cushion compression	High	Not in ISO 7176
	Exposure to fluids causes deterioration	Chemical resistance and waterproof testing		Not in ISO 7176
	Tearing and wearing of cushion and cover, loosening upholstery	Durability: ageing, tearing, abrasion, loosening		Not in ISO 7176

Table 4 (continued).

Footrest	Broken footrests	Durability: strength	High	ISO 7176-8
	Difficulty in folding, adjusting for height	Durability: corrosion		Not in ISO 7176
Brakes	Loosening and corrosion of locking mechanism	Durability: cyclic testing, ageing, corrosion	Low	Not in ISO 7176
Frame and cross braces	Bent push handles	Durability: loading	Low	Not in ISO 7176
	Wear on coatings, coating deterioration	Paint chipping and corrosion		Not in ISO 7176
	Rusted holes, welds and areas where paint is chipped off	Durability: corrosion and testing folding mechanism		Not in ISO 7176
Fasteners and arm pads	Bolts and pads loosen out	Loosening	Low	ISO 7176-8
	Pads deteriorate, exposing edges	Ageing and abrasion testing		Not in ISO 7176
	Rusted components	Durability: corrosion		Not in ISO 7176

Casters and rear wheels were selected as crucial components for testing and test method development since they break down quickly in LRS. Corrosion was identified as a factor that affects most wheelchair parts and was likewise prioritized for testing. Testing a complete wheelchair through simulated environmental conditions was as a recommendation by the ISWP-SWG.

1.2.3 Discussion

Current ISO testing methods simulate conditions for urban paved environments and thus, development of additional test methods is been recommended for LRS based on typical conditions seen there [1]. Following this recommendation, a prioritised list of tests was is developed in this study through a literature review and feedback from expert advice to help predict wheelchair failures.

There is little representation from less-resourced countries on the ISO technical committee, and consequently, test methods do not completely reflect conditions seen in such countries. While WHO guidelines suggest using ISO 7176 as the basis to develop new standards [1], no new standards that specifically address the performance issues of wheelchairs in LRS have been proposed. A few countries having LRS have implemented the standards, but no formal reports were found indicating their implementation.

The ISO testing studies included in this review were conducted in an independent testing laboratory mostly on wheelchairs provided in RS. Results from Table 1 show that manual wheelchairs overall lack standard product quality, especially HWCs that resemble the majority of designs distributed in LRS [22, 43, 49, 79]. Around 70% – 90% of HWCs failed to pass minimum durability requirements [71, 73, 79, 80]. Similar wheelchair designs produced in LRS [79, 80] failed prematurely. Higher incidences of Class III failures with HWC designs indicate higher rates of breakdown and repairs during use, which is evident from anecdotal reports [17, 19, 27] and reviewed field studies [47, 80, 88, 89]. On the other hand, UWC designs were found to be durable and experienced fewer frame failures with ISO tests. This test outcome was predictable because UWCs are sophisticated wheelchair designs with superior quality materials that are designed for performance in developed environments and ISO durability tests subject wheelchairs to conditions that simulate such environments [1, 18]. Field evidence with active users in RS has been reported with UWCs which shows positive satisfaction and fewer repairs in last 6 months of use [73]. However, these designs are not suitable for LRS owing to high costs associated with their materials and manufacturing. Overall, it can be concluded that ISO durability tests are suitable to test wheelchair designs like HWCs that break prematurely and UWCs that are developed for performance in RS.

Field evaluation studies have been carried out with ISO-qualified wheelchairs appropriate for LRS. Four such field studies reported failures, repairs, replacements and missing parts over 2 weeks to 8 months of field use [29, 53, 83, 84]. Wheelchairs in two of these short-term studies were provided based on WHO guidelines, maintained frequently and favoured by the users [53, 84]. One study [82] assessed ISO-tested appropriate wheelchairs after 1–2 years of use which were provided without user training and serviced occasionally. Several part failures were found that would require a technician’s attention (see Table 2). Findings from these studies demonstrate that failures occur on ISO-qualified models with everyday use especially with parts such as brakes, tires, seat covers, casters, footrests and armrests. Field failures can be associated with product properties such as substandard material quality, poor parts selection, inappropriate design and manufacturing inconsistencies. These properties can vary with the locally produced versions of certain ISO-qualified wheelchairs like the Whirlwind Roughrider which makes them prone to early failure. Moreover, LRS have harsh environments which can degrade products rapidly. ISO test qualification is representative of 3–5 years of outdoor use [59, 67] but apparently falls short of qualifying products for LRS use based on reviewed study results. Accurate prediction of life duration of certain wheelchair parts may not be guaranteed.

Field studies that provided wheelchairs as per WHO guidelines [53, 84] indicated that appropriate services, user training and regular maintenance are necessary to reduce the rate of field failures. However, LRS struggle with capacity for appropriate services. Provision of user training, funding and access to repair services is limited [1, 17, 18, 20, 27, 28, 53] which was evident in field studies as well [29, 82, 83, 88, 89]. In the wake of such concerns, international efforts focused on increasing capacity and improving service provision in LRS are ongoing [57]. While such efforts are in progress, it is equally necessary to develop products with greater reliability and higher durability to reduce failure occurrences and prevent breakdowns. This perspective has been shared by the WHO guidelines as well that stress the parallel need for appropriate services and high-quality products [1, 14]. Development of durable, high-quality products, in turn, calls for development of rigorous test methods which were identified in this study.

1.2.3.1 Wheelchair failures

Failures seen with ISO testing in the laboratory were similar among wheelchair designs. Fractures with cross braces, side frames (at weld joints), backrests, caster spindles and footrests were found to be common in these studies [69-80]. Failures were influenced by frame design, wheelchair material, screw holes, welding techniques and caster and tire characteristics. However, failure modes observed with ISO testing are rare in the field based on field failure evidence gathered through literature review and failure evidence provided by ISWP-SWG members. Dominant field failures found in LRS are flat and cracked tires, wobbly rear wheels, bent frames, non-functional brakes, worn out bearings, damaged armrests, torn seat covers, loose upholstery, collapsed cushions and rusting and loosening of several parts. Any representation of these failures is not evident in ISO testing results which mostly produces fracture failures caused by impacts on MDT and CDT. These differences are likely attributed to the fact that ISO Section 8 tests do not include environmental exposures that occur in the field. To accurately predict failure modes and life duration of products for LRS, it is necessary to develop additional testing methods for LRS with relevant test conditions. ISWP-SWG experts echoed similar advice.

1.3 ADDITIONAL TEST METHODS

The product testing matrix developed through consensus of experts highlights the requisite test factors (conditions) for testing products for LRS. The matrix assisted in development of additional test methods. Based on availability of resources and capacity for development with ISWP partners in the SWG, four test methods were given high priority – caster durability testing, rolling resistance testing, corrosion testing and whole chair testing.

Caster failure was noted as a top concern in the field as per ISWP-SWG experts. Casters experience a variety of failure modes with tires, bearings and stem hubs and ISO tests primarily subject casters to vertical loads and stresses. Hence, experts suggested that caster durability testing should be conducted separately. Incorporating amplified and angular loading patterns along with corrosive conditions and various types of simulated surfaces including sand, mud, gravel and stones was recommended for the new caster test method. Such testing is estimated to screen caster designs for greater durability, requiring less maintenance and incurring fewer repairs in LRS.

Corrosion of wheelchairs was observed as a critical concern because several wheelchair components are unable to operate after being corroded. Although ISO testing includes climatic testing of wheelchairs in hot and cold environments for power wheelchairs, it does not simulate moisture and acidic exposure that occurs for all wheelchairs. It is known that corrosion adds to the effect of fatigue during field use for certain wheelchair parts like bearings [91]. This calls for conducting fatigue and corrosion testing simultaneously. Experts recommended corrosion evaluation of the complete wheelchair similar to already established standards like ASTM B117 [92].

Resistance to wheelchair rolling was also identified as a major performance issue in LRS. While resistance characteristics for rubber on different surfaces are known to an extent, propelling wheelchairs over a variety of surfaces requires a significant user effort [17, 53, 90]. Wheels experience a range of rolling resistances based on variation of elastic rebound between the tire and different surfaces, tire tread design, type of tire (pneumatic vs. solid), camber angle, toe-in and toe-out alignment, type of spokes and characteristics of the axle hub bearings. Casters are also known to have greater rolling resistances based on tire diameter, characteristics, surface, the type of materials used and bearing efficiency. Thus, testing to evaluate the rolling of wheels and casters, which is not a part of ISO 7176, is being considered in the new test methods. Comparing the rolling resistance of different types of available wheels and casters is needed to develop rolling resistance specifications for models and guidelines for selection of wheels and casters.

The ISWP-SWG recognises that the entire wheelchair suffers from different types of loads and effects of environmental factors causing wear (rough surfaces, ultraviolet light, high temperature, dirt and dust) and corrosion (humidity and water exposure). Testing the wheelchair against combined effect of these test factors is suggested to replicate field failures.

1.3.1 Limitations

The study pulls evidence from ISO testing studies and field evaluation studies combined with expert recommendations to determine the gaps in testing, and to develop a prioritized list of new testing methods that are needed. Based on the review, a low level of evidence for products used in LRS is available to inform additional test development. Twelve research articles were included in this literature review on wheelchair testing and only two studies reported results with wheelchairs used in LRS. Although the USAID report [30] on wheelchairs recommends ISO testing of wheelchair designs appropriate for LRS, full-fledged ISO testing studies with such designs are not yet conducted. Findings from such studies could have assisted in understanding the failures found in the laboratory and directed the additional test development.

Field evidence in the review was limited in many respects. Numbers of failures, repairs and replacements were provided in four studies out of which two were conducted in a rehabilitation facility and two evaluated HWCs [47, 53, 80, 84, 86, 87]. Remainder of the studies only reported failure modes. There was a lack of evidence on whether failures led to breakdowns (usually caused by severe damage to frame, caster or rear wheel) except for one study on donated wheelchairs [88]. Several studies involved modifications to the products prior to evaluations which could have affected the failure outcomes [47, 82]. Nearly all studies with ISO-qualified appropriate models [29, 47, 80, 82] involved paediatric populations whose functional requirements from a wheelchair, use practices, hours of use per day, method of propulsion and maintenance abilities are different from the general population. In a broader population of adults, it is expected that failures would occur faster and would be more severe compared with those of children. There were no long-term studies which could have allowed for better comparison between failures in the field and those that occur during ISO tests. Also, no comparison studies were found between performance of wheelchairs in RS and LRS.

As expert advice was sought in this study, there is a potential for expert bias in this study. Photographs collected as evidence were only available from end-of-life chairs which may indicate extreme damage to the part, with limited knowledge of the age or conditions of use of the chair.

1.3.2 Future work

Following development of test methods, the ISWP-SWG group plans to suggest new test methods to the ISO standards committee as a new or revised ISO 7176 standard or as a technical specification so that they are harmonised with national standards. Product quality testing using these additional standards could then be included as part of regulatory policies that governments of less-resourced countries adopt, or as part of the WHO GATE initiative. Validation of the new test methods is an important step to assess correlation with performance seen in the field and it will be conducted through research studies in LRS in collaboration with manufacturers and charitable organisations. Manufacturers and wheelchair designers in LRS will be encouraged to implement ISWP test methods for testing newly designed parts, custom components and wheelchair prototypes. Parts with low testing priority will be tested as resources are available.

1.4 RESEARCH GOALS

This dissertation research work is driven by the need for additional wheelchair standards highlighted by the WHO Guidelines and focusses specifically on development and validation of the caster testing protocol.

The work was initiated with the development of a caster testing system in the laboratory. The product testing matrix developed by the ISWP-SWG for casters assisted in establishing the specifications for the system. Chapter 2 details the development of the testing system, the iterative design process, the testing equipment, and the preliminary testing carried out with the caster models used in LRS. Preliminary testing exposed weak links in the caster designs that were tested. Results were compared with anecdotal reports from the manufacturers. Design improvements were suggested to them.

Following development of a reliable testing system, the focus shifted towards validation of the caster testing protocol. As a part of the validation process, the testing factors employed in the protocol were validated to outdoor exposure and laboratory testing results were compared with outdoor performance and failures of casters. For this purpose, two studies were carried out.

Lack of a tool to characterize how casters fail in the field motivated the development a new tool. Chapter 3 describes the development and validation (face validity and test-retest reliability testing) of the caster failure checklist that contains common failure modes seen with casters. Test-retest reliability testing was conducted with two cohorts who used the checklist to rate caster failures. One cohort (n=10) rated failures through physical inspection and the other one (n=13) reviewed failures online.

The second study focusses on validation of the caster testing protocol. Exposure with three testing factors of shock, corrosion and wear was correlated with corresponding outdoor exposures. Chapter 4 presents the investigation from acquiring data and samples for conducting the correlation experiments to simulating the testing conditions on the caster testing system. Further, the chapter includes testing casters with the validated protocol and comparison of lab-based caster failures with outdoor failures.

The last chapter, Chapter 5, summarizes the findings from the dissertation work and provides recommendations for product testing and implementation of testing standards in less-resourced settings.

2.0 DEVELOPMENT OF A WHEELCHAIR CASTER TESTING SYSTEM AND PRELIMINARY TESTING OF CASTER MODELS

2.1 INTRODUCTION[2]

Wheelchair casters are a common point of failure in adverse conditions. As noted in the previous chapter, they travel over a variety of rough surfaces and rocky terrains in less-resourced settings (LRS). Most LRS fall in the tropical zone [93] and experience high temperature and humidity, which adversely affects product durability. Moreover, wheelchair use conditions evident in LRS impose greater quality requirements on products, which are known causes for wheelchairs to fail prematurely [18, 22, 42, 86-89].

A variety of casters designs (see Figure 5) are used on wheelchairs, and the demanding operating conditions in LRS cause these casters to fail in different modes as shown in Table 5.

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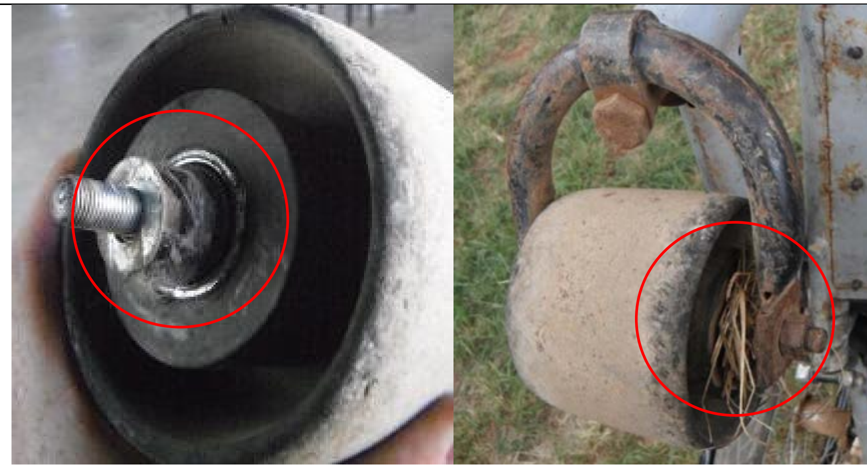
[2] This Chapter is published in the manuscript "Development of wheelchair caster testing equipment and preliminary testing of caster models" in the African Journal of Disability. By Anand Mhatre, Joseph Ott and Jon Pearlman.

Figure 5. Caster designs used on wheelchairs

Table 5. Caster failures seen in the field

Caster Failure Modes	Pictures of Failures
1. Fracture failure	 Failures: Fracture in caster wheel spoke (left), axle bearing fracture (center-left), stem bolt fracture (center-right) and stem bearing fracture (right)
2. Corrosion failure	 Failures: Corrosion of stem assembly (left), fork (center-left), axle bolt (center-right) and axle bearing (right)

Table 5 (continued).

3. Dirt ingress and debris causing obstruction to caster rolling	 Failures: Resistance to rolling caused due to strings (left) and debris (right) caught in caster axles
4. Tire Failures	 Failures: Tire-roll off (left), tire etching (center-left and center-right) and tire deflation (right)

Caster quality issues have been found during durability testing with ISO 7176 standard Section 8 that includes static, impact and fatigue tests [60]. Casters are known to undergo fracture failures throughout such tests. Fractures with caster's vertical stem assemblies are common [69-73, 94]. Fractures with the caster fork, bearings and wheel spokes have been reported too, as have alignment issues with the caster wheel [72, 80]. Additionally, failures and repairs with casters have been noted in field studies that evaluated usability and performance of wheelchair products [47, 53, 82, 86, 88, 89]. In one study conducted in India, casters were found to be a constant source of worry; Saha et al. reported breaking caster wheels and forks, missing tires and bolts, locking of the casters while rolling, bearing failures and excessive caster vibration with LRS- produced chairs [89]. Casters sinking into soft ground and failure while climbing over obstacles were some of the performance issues caused by inappropriate product design. Premature wheelchair breakdown occurred, as casters were found to not last more than 6 months. Two recent studies conducted in Kenya reported worn-out caster tires and damaged bearings within 1–2 years of use [82, 95]. A cross-sectional study conducted in the United States with wheelchair users (n=109) that looked at relationship between caster design and adverse consequences found that casters suffered more failures among other wheelchair parts (almost 1/3rd of all failures) and wheelchairs with small-size, solid casters were significantly associated with tips and falls out of chair (p=0.024). Most caster failures are known to cause user discomfort, adverse incidences such as accidents leading to user injuries and wheelchair breakdowns [46] Breakdowns can cause long term loss of mobility and affect the user economically and socially.

The WHO Guidelines and the stakeholders and experts at the wheelchair consensus conference recognize the quality issues with wheelchair and casters. To address them, the guidelines recommend additional testing based on outdoor environmental and use conditions [1, 18]. The development work for additional tests was taken up by ISWP's Standards Working Group (ISWP-SWG) [13]. This group was formed to enhance product quality, as well as to develop standards and resources to promote appropriate high-quality products for delivery in LRS. Among the additional tests that the group has proposed, caster durability testing was ranked (through consensus voting) as one the most critical areas for testing [13]. This study covers the design process followed for developing new caster testing equipment and the preliminary testing conducted with different caster designs.

2.2 METHODS

The development of additional tests commenced in early 2015 after the ISWP-SWG discussed the concept. The group members reported several wheelchair parts failures evident in LRS, identified factors that contribute to field failures and evaluated whether these factors are included in ISO 7176 fatigue tests of MDT and CDT. The results of this evaluation for casters demonstrated the lack of requisite test factors in standard testing of caster assemblies which implied developing a new testing method.

For developing additional tests, the ISWP-SWG was divided into subgroups and the caster testing subcommittee led the development of new caster testing method. Searches were conducted for standards available for caster assembly testing. The results were obtained and reviewed by the author for relevant testing methods. Other testing methods for wheelchair casters were retrieved from literature review work conducted by the author previously [13]. ISWP-SWG members reported on caster testing systems developed by wheelchair manufacturers. Testing methods retrieved from different sources were evaluated for presence of testing factors pertaining to LRS conditions. The result of this search process informed the group that a new testing system needs to be developed.

The caster test design process began with ISWP-SWG experts putting together the functional requirements for the new testing method. The requirements were based on the gaps in current caster testing methods (ISO and other standards) and the expected testing conditions corresponding to LRS use. The members of the caster testing subcommittee (Table B 1) developed design concepts accordingly. Feedback on the designs was taken in three steps. Firstly, through ISWP-SWG discussions, the advantages and disadvantages of each concept were discussed in detail and a single design for further development was selected. Secondly, the designs were drafted in detail and a second round of feedback was conducted through an in-person meeting with all ISWP-SWG experts. Design improvements were provided. Finally, the design was refined according to the recommendations, benchmarked to MDT test conditions, and further feedback was sought from the machine shop staff at the Human Engineering Research Laboratories (HERL) [96] where the final design was to be fabricated. Following approval from different contingents, the equipment was fabricated at HERL over a period of 2 months.

To evaluate testing feasibility and efficiency of the new equipment, models of casters differing in sizes and parts' designs were tested initially. Four caster models were tested for defined number of test cycles under known weight. As impacts in the field are at different angles, casters were subjected to oblique slat impacts, except one model which was tested for square slat impact (with slats fixed at zero-degree angle). Following reliable performance of the new equipment, a preliminary testing study was carried out with six caster models to evaluate the durability of casters with two obstacle conditions. Four samples of each model were tested. For each model, two samples were subjected to square impacts (zero degrees) and the other two to oblique impacts at 30 degrees (±1.5% error). Casters were tested under known weight until failure in this study. A paired samples *t*-test was carried out between the two slat angle conditions for each model. Caster assembly failures were documented and analysed. Feedback was sought from respective caster manufacturers about the failures seen on the caster test and how they compared to failures commonly found in the field. Results of this testing informed the caster testing subcommittee of necessary modifications to the caster testing protocol.

2.3 RESULTS

2.3.1 Field failures of caster assemblies

Outdoor conditions leading to field failures of casters were identified by ISWP-SWG experts. Comparing different test factors corresponding to each outdoor condition with the testing conditions on ISO 7176 fatigue tests of MDT and CDT yielded results as seen in Table 6. Several test factors of interest were not included in standards testing.

Table 6. Caster assembly failure modes and corresponding quality-affecting factors as seen in the field

Failure modes	**Outdoor Factors**	**Factor inclusion status in ISO 7176**
Broken and bent caster parts	Impacts and loads, fracture loads, oblique impacts	Yes (ISO 7176 – 8), but MDT and CDT do not reproduce complex load conditions that occur in LRS.
Corrosion in bearings and on metallic parts	Corrosion due to high humidity environments	Not in ISO 7176
Worn out tires	Abrasion due to rougher terrains	Not in ISO 7176
Tire puncture	1. Rocky surfaces 2. Poor air retention capability of the tube in tire	Not in ISO 7176

Table 6 (continued).

Parts degradation	Accelerated aging due to ultraviolet light (UV), high temperatures and rough surfaces.	Not in ISO 7176
Fluttering caster	Caster flutter on rocky surfaces at high speed	Seen on MDT but not tested for.
Worn out bearings	1. Poor lubrication, seal design & quality 2. Heavy impacts	Not in ISO 7176
Dirt and dust in bearings		
High rolling resistance	Design of caster parts not applicable to LRS	Not in ISO 7176
Caster caught in obstacles	Design of caster parts not applicable to LRS	Not in ISO 7176

2.3.2 Review of caster standards, testing literature and existing test methods

Caster testing standards have been published by the ISO and the American National Standards Institute – Institute of Caster and Wheel Manufacturers (ANSI-ICWM) [97]. ISO 22877-82 covers standards for casters for institutional use such as furniture and swivel chairs for use in shops, restaurants, hotels, educational buildings and hospitals [98]. ISO 22883-84 is suitable for casters used in industrial environments [99]. The ISO standards contain methods for fatigue and performance testing of caster braking system but testing methods for durability testing of the entire caster assembly have not been included. The ANSI-ICWM standards contain static load tests, side load tests and vertical impact tests for industrial and institutional casters [97]. Dynamic tests are included, and they qualify as durability tests. They require casters to roll over obstacles (obstacle height based on caster diameter) and multiple track configurations that include a linear track, circular track (horizontal position) and circular track (vertical position). Testing methods that were found in the literature are listed in Table B 2.

The development of caster testing machines by two wheelchair manufacturers was reported by ISWP-SWG members. These included weighted casters mounted on a drum with a slat (similar to MDT test) as shown in Figure B 1 below. However, caster testing methods with appropriate test factors relevant to field use in LRS were not found in the standards, literature or any searches.

2.3.3 Development of new caster test system

Following review of existing caster testing methods, the ISWP-SWG decided on developing new caster assembly testing equipment which could incorporate relevant testing factors. Outcomes from comparison in Table B 3 assisted in developing the functional requirements of the new system. They are as follows:

(1) The new testing system subjects casters to straight and oblique impacts.

(2) The new testing system exposes casters to a variety of surface patterns to simulate LRS terrains. Replacing a surface during testing should be easy and require minimal time and effort.

(3) The new testing system exposes casters to moisture/water to simulate corrosion failures.

(4) The new testing system tests casters of different designs at the same time for comparison testing.

(5) To simulate appropriate caster behaviour, the new testing mounts caster for testing similar to the way it is mounted on its wheelchair.

(6) The new testing system is flexible to change speed and direction during testing. The optimal speed recommended for this test was 1 m/s (same as MDT).

(7) The new testing system allows a range of weights for loading on casters.

(8) The new testing system includes an accelerated wear test for casters.

(9) The new testing system replicates failures as seen in the field.

The caster testing subcommittee members developed design concepts based on functional requirements. Six concepts were proposed (see Table 7) and modelled for initial evaluation by the ISWP-SWG. Advantages and disadvantages of each were discussed for selecting an appropriate concept for design and development.

Table 7. Caster concepts suggested for equipment development.

Concept Description	Advantage	Disadvantage
1. Weighted caster(s) mounted on a treadmill with bumps and rough surfaces.	Reliable system for exposure to different load conditions.	Durability concerns with the treadmill belt; it is difficult to retain rough surfaces and bumps on a rotating belt over time. Like MDT, stem bearings may not be tested as casters don't swivel about stem axis.
2. Weighted caster(s) tested on a reciprocating table with bumps and rough surfaces.	Change in direction is useful for testing the stem bearing assembly of the caster.	Testing multiple casters with reciprocating movement (at a speed of 1m/s) would require a larger surface area.
3. Weighted caster(s) rolling on a heated drum (like MDT) with rough surfaces and slats (bumps). The caster is exposed to acidic, salt spray and UV light while running on drum.	Concept to incorporate different test factors at same time. Reliable system for testing.	Attaching different surfaces to drum's surface is difficult. Replacing surfaces quickly during testing can be difficult and will require more time. Heating the drum is a mechanism. Salt spray and UV exposure affects strength of the test equipment.
4. Weighted caster(s) turning in a circle like a carousel over different rough surfaces and bumps on a table. The casters are mounted on arms that are attached to the center shaft. (See Figure B 2)	Different surfaces and loads can be switched during testing. Speed and direction of the shaft changes.	Heavy weights on rotating casters at 1m/s may be unsafe. The behavior of a revolving caster after hitting a bump depends on speed, moment of inertia around the stem axis and load. The caster can swing out abruptly after impacts, which may not be representative of outdoor behavior of casters.
5. Concept #5 is similar to #4; in this concept, the casters are stationary, and the table rotates. (See Figure B 2)	Advantages are similar to concept #4. As casters do not revolve, they may swing out moderately.	Exposure to several test factors like humidity, UV and high temperature may be difficult with this setup as it can possibly degrade the equipment.
6. Concept #6 is similar to #4 above but the entire assembly is enclosed in a drum at an angle and partially filled with water.	Advantages are similar to concept #4. Consistent exposure to moisture.	Disadvantages are similar to that of concept #4. Weight on top of the caster will not be same at different points of travel and the caster may swing inward/outward (based on position) due to gravity after hitting bumps. Casters can remain wet throughout the test, which is not typical in outdoors.

The concept #5 (turntable system design) was selected for development because of its advantages. It was drafted in SolidWorks [100] and was reviewed comprehensively in an in-person meeting with ISWP-SWG. Design recommendations (Table 8) on the turntable and caster mounting were provided by the group and were prioritised for incorporation into the design (see Figure B 3).

Table 8. Design recommendations by ISWP-SWG for turntable test design

Design Features	Recommendations
1. Turntable	1. Larger area to accommodate 4 large size casters (about 8 inches in diameter). 2. Able to change the surfaces on the turntable immediately. 3. Mount the drive motor on top of the turntable to avoid any water or dirt exposure from testing.
2. Caster arm	1. Weight on the caster = 30-35% of user weight.
	2. Variable length of suspension arm so that caster is mounted at wheelbase length of the wheelchair.
	3. Measure angle offset to the vertical and mount the caster at an angle on the arm accordingly. 4. Clamp the rod holding the caster arm assembly on the pillars of the equipment. 5. Use sensors to detect the descending arm following fracture of any caster assembly.
3. Design Considerations for environmental test factors	1. Use UV lamps for aging the casters. Test the aging of rubber tires. 2. Include gravel for testing and employ a shaker underneath. Maintain continuous agitation and level the gravel consistently. 3. Include dirt ingress testing as per standards. 4. Develop a tank around the table that can contain water for humidity exposure.
4. Test suggestions	1. Increase number of test cycles compared to MDT. 2. Increase the height of bumps (i.e. MDT slats on drum) for testing casters. 3. Introduce damping to eliminate caster bounce.
5. Precautions	1. Monitor temperature of the casters and avoid overheating them. 2. Conduct an inspection of the casters at specific intervals.

The author benchmarked the design with MDT test, developed design specifications (see Table B 3) and modified the design accordingly. One rotation of the turntable is twice the distance the caster would travel on MDT.

Feedback from machine shop staff at HERL was related to operation and fabrication of the test equipment. Three important suggestions were received as shown below. Figure 6 shows the final drawing prior to fabrication and assembly of the caster test equipment.

(1) Include a gearbox (speed reducer) for rotating the turntable.

(2) Deploy corrosion resistant rollers beneath the turntable to reduce the risk of rusting.

(3) Place crossbars under the turntable assembly to strengthen the equipment foundation and reduce any movement between the vertical angle iron bars.

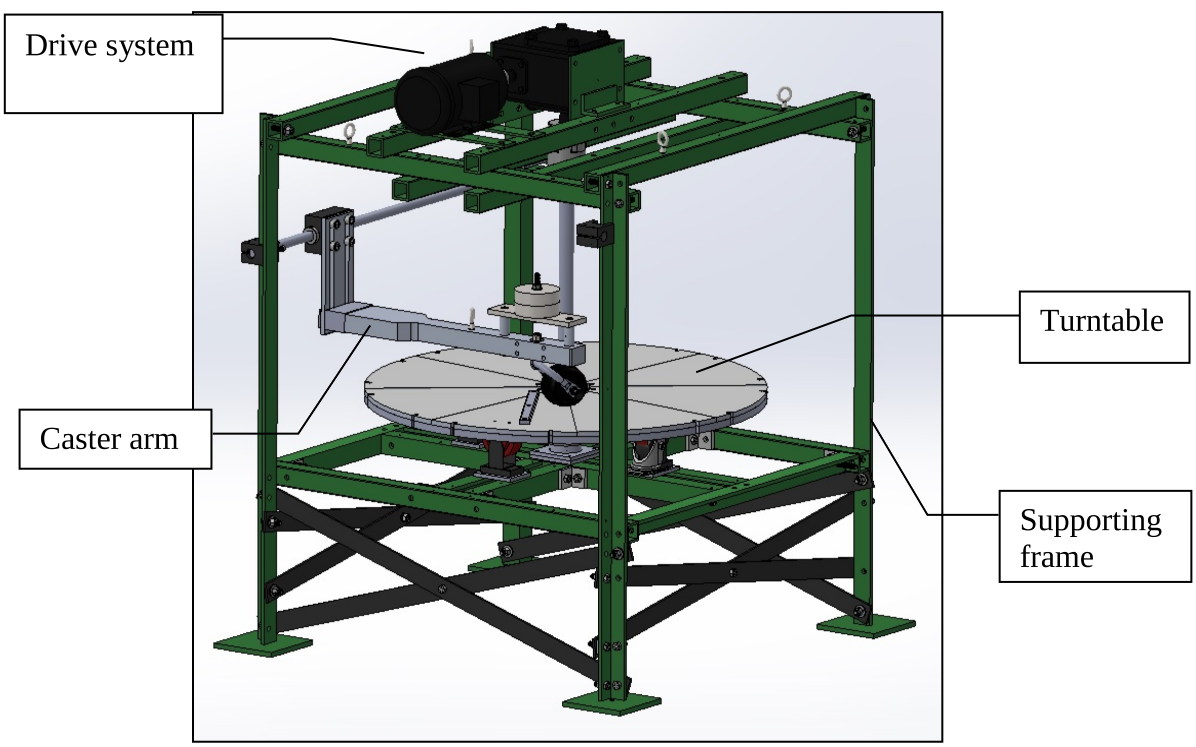


Figure 6. Final caster test equipment drawing for fabrication (includes only one caster support arm)

2.3.4 Caster test equipment description

The test equipment can be divided into four modular designs: (1) drive system, (2) supporting frame, (3) turntable assembly and (4) caster arm assembly.

The drive system consists of a motor, gearbox, motor driver and system controller connected to an LCD display. The gearbox and motor selection were based on the power requirements and functionality of the test. A 2HP reversible induction motor (model# MTR-002-3BD18) from Automation Direct [101], 40:1 ratio gearbox (model# 13-325-40-R) from Surplus Center [102], AC motor drive (model# FM50) from Teco Westinghouse [103] and a Micro820 Programmable Logic Controller System from Allen Bradley [104] were selected. The motor driver was programmed manually based on the direction and speed requirements of the turntable system, and the system controller was programmed using the Connected Components Workbench [105]. Three different programmes were developed – (1) one directional turntable rotation similar to MDT; (2) one directional rotation with a reverse cycle after a specific number of turns; and (3) a continuous clockwise & counter clockwise rotational movement of the turntable. The electrical wiring diagram for the caster test is shown in Figure 7. The third controller programme is shown in Section B.1. The LCD display shows the test programme, the status of test and the number of test cycles completed. The motor driver, the system controller and the LCD display are housed in an enclosure as shown in Figure B 4.

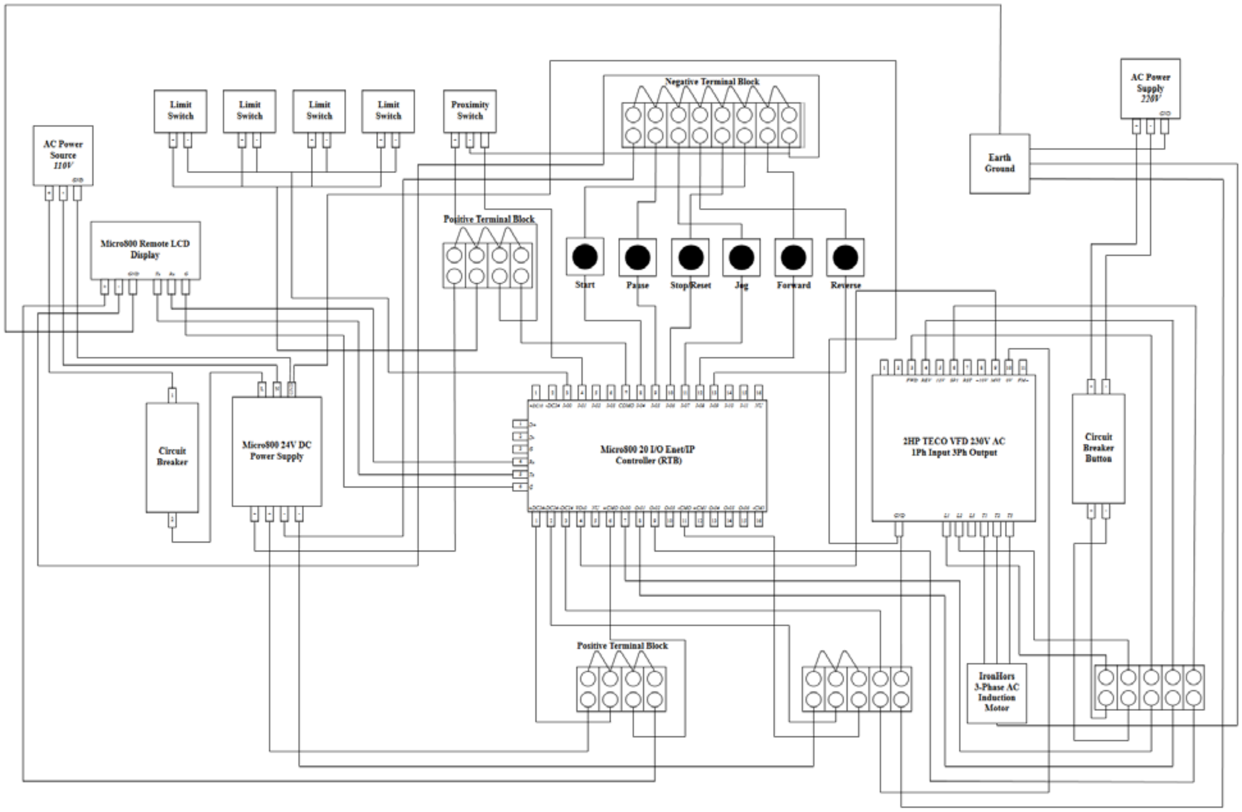


Figure 7. Electrical wiring for the caster test

The frame consists of four vertical angle iron bars of 4 and half inch height that are connected by a web of steel square tubes and angle irons on the top and below the turntable. The top web supports the motor, gear reducer and flanged bearing, and the one below the turntable supports the rollers and shaft bearing housing. To strengthen the foundation and eliminate movement of vertical bars, flat steel crossbars have been attached.

The turntable (Figure B 5) is a 40-inch diameter circle cut from three-quarter inch aluminium plate. The turntable is connected to the gearbox with a long shaft through a flange-mounted ball bearing (for support) and a Replaceable-Center Flexible Shaft coupling. The shaft is mounted on a thrust bearing under the table. Polyurethane rollers support the turntable rotation from underneath and absorb the impact from casters bouncing on the turntable. Flange couplings attach the turntable to the shaft. Eight half-inch thick pie-shaped pieces are clamped to the turntable on top. They serve as plates for accommodating different surface patterns and are currently used for holding slats at desired angles.

Initial design of the assembly included a 2-inch thick caster arm attached to a vertical member that could slide on block holding a steel rod as shown in Figure B 6. The caster's stem bearing assembly (to be tested) is accommodated inside a housing attached to the arm, and barbell weights are mounted on top of the arm. The arm hinges on the rod that has its ends clamped to the angle iron uprights, and the position of the rod can be adjusted vertically along the length of those uprights. The maximum wheelchair axle height that can be simulated is about 22 inches. The initial arm design was not flexible enough to position caster designs of variable diameters on the orthogonal axis of the turntable; therefore, the design was revised with 8020 components [106].

Fracture failure of casters during testing could result in the caster arm to falling on the turntable crushing the caster or damaging the turntable. To immediately detect the fall, a limit switch with rotating lever is mounted above of each the caster arms and strings are used to connect the lever from the limit switch to an eyebolt on the arm (see Figure 8 below). For appropriate detection of failure and avoiding any damages, a safety strap is used to prevent a vertical drop of the arm after a failure and hold the arm while the limit switch is triggered. Figure 9 shows the new caster testing equipment that was fabricated and assembled. The parts were powder-coated green and black for aesthetic appeal and to reduce the risk for corrosion.

Figure 8. Limit switch for detecting caster arm fall.

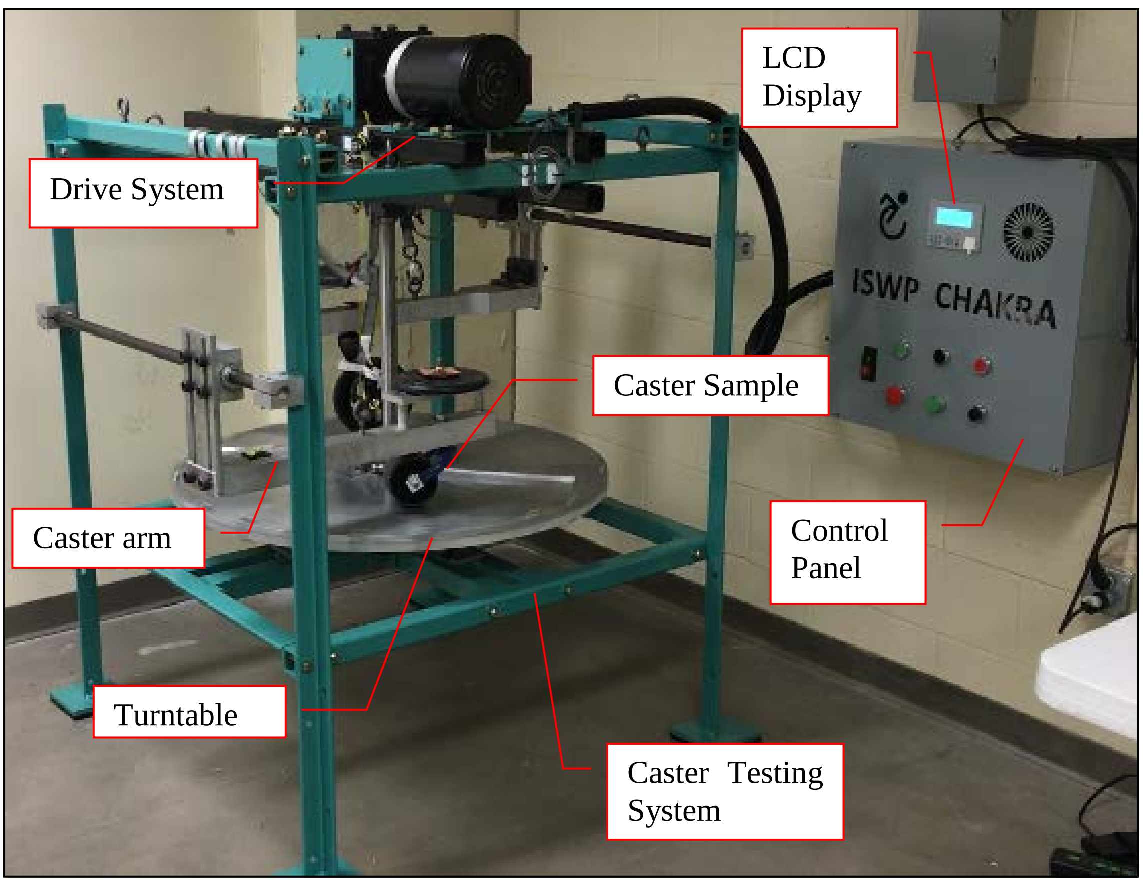


Figure 9. ISWP Caster Assembly Test

2.3.5 Feasibility testing results

Four caster designs with solid tires as shown in Figure 10 were tested first. This initial testing to verify reliable performance of the new test equipment was conducted with 20lbs ± 1lbs weight (minimum load reported on casters) on each caster and 100,000 test cycles. A total of 100,000 cycles were chosen as it is equivalent to 200,000 MDT cycles which is the minimum qualification requirement for wheelchairs [60]. Results from initial testing are shown in Table B 4.

Figure 10. Caster assemblies tested in initial testing phase (Models A-D from left to right)

2.3.6 Preliminary testing results

Preliminary testing to evaluate the effect of square versus oblique slat impacts was conducted with 31% ± 1% lbs weight on caster models (see Figure 11) and 500,000 cycles. Caster design C from initial testing was used in this study because of availability of samples. Weight selection was based on ISWP-SWG recommendations and the availability of weight plates because weight carried by casters typically ranges between 20 and 40 lbs [107-110]. A total of 500,000 test cycles were selected because MDT testing until failure is conducted until 1 million cycles, which is five times the minimum number of required cycles for testing [71, 94]. To avoid caster shimmy during testing, stem assemblies were tightened such that the casters would not lock and reverse their direction smoothly when the turntable was reversed during the test setup. Additionally, for the preliminary test, the casters were placed away from the turntable centre at 11.5-inch radius which simulated about 3 years of regular travel at 1 m/s assuming an average user travels about 800 m/day [107]. Results of preliminary testing and manufacturer feedback on failures are shown in Table 9. Among the caster models, no significant differences were found between the number of cycles completed with square and oblique slat impacts ($p > 0.05$).

Figure 11. Caster assemblies tested in preliminary testing study (Model A and C are not shown)

Table 9. Preliminary testing results with different caster designs

Caster	Cycles Completed	Failures	Field Failure	Pictures of Failures
A1	38,726	Stem bolt fractured.	No	 
A2	500,000	Corrosion was noted on stem bolt due to grease coming out of the bottom bearing. Cracks seen in rubber tire due to heating.	No	
A3	55,204	Stem bolt fractured. Corrosion was noted on stem bolt due to grease coming out of the bottom bearing.	No	
A4	135,721	Stem bolt fractured.	No	
B1	400,243	Significant play was noted between stem bolt and fork, which caused the caster to bend. Cracks seen in rubber tire due to heating.	No	 
B2	500,000	Cracks seen in rubber tires due to heating.	No	
B3	500,000		No	
B4	500,000		No	
C1	30,548	Fork fracture at the stem bolt – fork connection	No	 
C2	71,763	Fork fracture	No	
C3	64,413	Stem bolt cracked. Tire cracked at 52,423 cycles.	Yes – tire failure	
C4	83,202	Fork Fractured	No	

Table 9 (continued).

D1	29,160	Stem bolt fractured at the stem bolt-fork connection.	Yes	
D2	26,080	Stem bolt fractured at the stem bolt-fork connection.	Yes	
D3	17,389	Stem bearing fractured	No	
D4	60,723	Stem bolt fractured at the stem bolt-fork connection.	Yes	
E1	6,127	Fork fractured	Yes	
E2	14,209	Stem bolt fractured	No	
E3	9,623	Fork Fractured. Crack was also found to initiate from the stem-bolt-fork connection that was rusted.	Yes	
E4	12,321	Stem Bolt Fractured	No	
F1	28,124	Stem bearing fractured	Yes	
F2	18,763	Stem bearing fractured	Yes	
F3	9,874	Stem bearing fractured	Yes	
F4	31,421	Stem bearing fractured around 9,000 cycles. The caster could no longer stay vertical on the tester as the bearings became loose.	Yes	

Note. Caster designs with suffixes 1 and 2 are subjected to square impacts whereas 3 and 4 are subjected to oblique impacts.

2.4 DISCUSSION

Less-resourced environments demand greater durability from wheelchair products. For this reason, the WHO Guidelines recommend rigorous quality evaluation through tests that simulate LRS conditions [1]. Development of such tests has been undertaken by the ISWP-SWG and the group has prioritised caster durability testing owing to frequent caster failures.

Review of testing methods for casters showed that several standard tests are available. ISO 7176 durability tests – MDT and CDT are tests with reportedly good repeatability and subject casters to square slat impacts. Drum tests developed by wheelchair manufacturers for testing casters separately are similar. ISO and ICWM caster testing standards have been published for institutional and industrial casters but they are not applicable to outdoor use of casters with wheelchairs. Testing methods reported in literature test casters for durability with mechanical loads and impacts only. These methods did not include exposure to environmental and use conditions as seen in LRS which also contribute to the degradation in product quality and consequently failures. None of these tests simulated exposure to different surfaces, high temperature, humidity or UV light. Deploying such test factors in lab-based accelerated tests is important to reproduce accurate product lifecycle and failures.

Evaluating caster durability using a new testing method with relevant testing conditions was proposed by the ISWP-SWG. Based on previous experiences, experts deemed it difficult to revise the current ISO testing setup. Issues noted with such modifications were related to securing different surface patterns on the cylindrical surfaces of MDT drums and enclosing the testing setup in a chamber for environmental testing. Thus, the development of a new caster testing system was initiated. Functional requirements specified for the new system were largely based on the need for inclusion of environmental testing factors that were lacking in existing testing methods. Design concepts that were variations of the reviewed testing methods (ICWM standards) with additional design features were considered.

Of the design concepts proposed for selection, the turntable test design addresses several functional requirements and offers several advantages. Implementing testing factors relevant to conditions in LRS seems feasible on the setup especially with exposure to different surfaces. Pie-shaped pieces have the capability to incorporate various surfaces patterns that correspond to uneven terrains and are representative of exposure to muddy ground, gravel, sand and dirt. With the availability of eight pieces, casters can be exposed simultaneously to different surface types. These pieces are clamped to the turntable such that they can be replaced easily in minimal time if change in surface exposure is required. Slats can be attached at different angles for simulating straight and oblique hits from bumps and obstacles. Exposure to different surfaces and loads conditions in LRS is responsible for failures related to tire wear and etching and inducing low-cycle fatigue effects in caster parts such as the stem bolt, wheel and bearings. To reproduce such failures, new surface patterns and testing protocols, which are validated to actual outdoor exposure, need to be developed for the new turntable testing setup.

Caster stem assembly failures are common during the field use and standard testing. The quality of stem bearings can be evaluated on the new caster testing equipment because the turntable can reverse its direction – unlike MDT, which has casters run in the direction of wheelchair primary propulsion. The stem bearings can be tested by either having the casters roll in opposite direction for a certain number of cycles after designated number of forward cycles or having casters continuously change direction with to and fro rotating motion of the turntable.

The new test design allows caster exposure to environmental testing factors such as moisture exposure and UV light. To incorporate moisture exposure, immersing casters partially in water in a tank (see Figure 12 below) surrounding the turntable was suggested by the ISWP-SWG members. The water tank addition to design is yet to be implemented because of concerns regarding controlling for water characteristics such as temperature, oxygen content, level of exposure (which may not be repeatable) and risk of corroding of testing equipment. Another suggestion by one of the authors was deploying water sprinklers, which can draw water from a tank under controlled conditions and assist in reducing caster tire temperature during testing. Corrosion of caster assembly parts is a top concern, and the failure can be simulated on the turntable design with reasonable modifications. For simulating rapid aging, UV/heat lamps can be mounted beside each caster in an enclosure. Degradation of rubber tires and other plastic materials can be simulated in this manner.

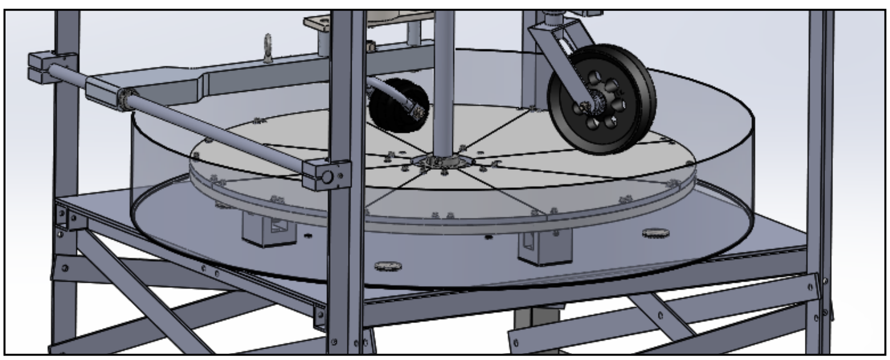


Figure 12. Incorporating water tank around the turntable

In sum, the caster testing equipment developed by ISWP-SWG caters to most functional requirements and has the capability to simulate different testing factors. To incorporate these factors, the test setup requires upgrades as stated previously.

Four different caster designs were tested to evaluate the feasibility of testing casters with the new system. Two caster models (one from a LRS wheelchair) completed the minimum number of test cycles, and the others experienced stem bolt fractures with crack initiation at an angle because of oblique hits. These fractures were anticipated failures as they are often seen with MDT. Reliable testing with the initial set of casters motivated testing caster assemblies for evaluating the effect of straight versus oblique impacts. The preliminary testing with models from wheelchairs used in LRS (except model B) revealed that slat impact angles do not have any effect on caster durability. However, it should be conceded that the sample size for testing against each condition was small, which could have led to a non-significant result. Also, oblique impacts on the caster can have lesser effect compared with square impacts, as the stem bearings allow the casters to swivel moderately to accommodate the impact. While there was no significant difference in number of cycles between two conditions for each model, the types of failures were relatively consistent.

Caster size was one of the differentiating factors among models during preliminary testing. Casters A and C have smaller diameters comparatively, and model A samples were found to be significantly affected from slat impacts causing stem bolt fractures. Stem bolt fractures are typical in caster assembly failures with MDT testing as noted in several wheelchair testing studies [70-73, 111]. These fractures initiate from the bolt surface where the bolt connects with the fork because there is only a minimal cross-sectional area to withstand the moment-force from impacts. Another cause for such failure can be grease leakage from lower stem bearings (seen with two casters) that rusts the lower part of the stem bolt and inner bearing rings. The rust-affected area can initiate cracks from the surface. The manufacturer of the model A caster disagreed with the test results as stem bolt failures have not been seen during field use.

The strength of caster models was affected by design factors such as tire thickness and hardness as well. While model A tires are pliable, the casters suffered greatly from slat impacts because the sidewall tires are not as thick. All large-size casters had significantly greater sidewall thickness, and among them model B was found to be more durable because the tires were able to absorb impacts. Tire hardness for caster B and F is 70A while other models have a hardness ranging from 78 to 90A. Hard tires were found to transmit the moment-forces from impacts directly to the stem bolt and fork connection, which causes bolts to shear. Model B caster parts (especially tire and fork) were reportedly expensive and high-quality, and hence, the casters endured the slat impacts without significant failures. However, this model did experience tire cracking failure after 500,000 testing cycles because of excessive heating of rubber. Tire failures such as cracking and wearing are common in the field with Model C casters as per the manufacturer. The caster test was able to simulate this failure for Model C in the laboratory; however, it should be noted that there are several other outdoor conditions apart from mechanical stress and heat that cause this type of failure.

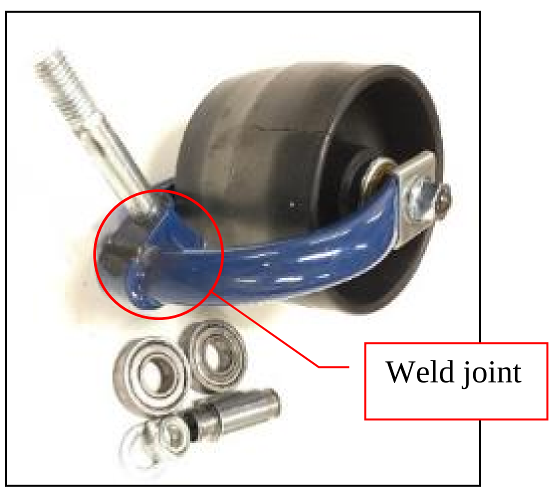


Figure 13. Fork weld joint on model C

A few caster models were found to undergo fork fractures during testing. Three caster C models, despite their sturdy rubber tire design for absorbing impacts, suffered fork fractures. On this model, part of the fork that accommodates the stem bolt includes a thin tube piece and a bent flat metal piece welded to rest of the fork. This welded joint shown in Figure 13 is constantly under tension. Thus, the fork design is found to shear from fatigue caused by slat impacts. The manufacturer of caster C reported that they have not witnessed fork fractures in the field. Model E incurred two fork fractures. Its polyurethane tires have 90A hardness and suffer significantly from impacts. The cross-section of the fork where the prongs connect with the centre piece of the fork has less material thickness, which is a cause for fracture. Models D and E are from the same manufacturer and have different tire designs and materials. The design of the stem-bolt and fork connection is same; the stem bolt is welded to a metal piece that holds the bolt against the fork. This welded connection was found to be a pain point because the weld cannot endure fatigue. The connection breaks prematurely, initiating a bolt or fork fracture. The rubber tires (85A hardness) on model D experienced rubber chalking which may cause them to gradually thin and eventually etch or crack. The manufacturer of models D and E acknowledged that the failures from preliminary testing were witnessed in the field occasionally, but they were not observed during MDT and CDT. Retesting the casters after an upgrade to the fork design was suggested to the manufacturer.

Stem bearing fractures were observed during preliminary testing, particularly with model F. The top stem bearing is a flanged cup thrust bearing that should accommodate vertical thrust from the caster. However, the outer ring material is made of low-strength steel, which causes these bearings to rupture. This failure happened quite early during testing and the casters were taken off only after they could no longer run vertically straight. The manufacturer of caster F admitted that bearing fractures have been noted in the field but they have happened after a year or two of use.

Overall, the failures observed with 50% caster models during the preliminary testing study were representative of their field failures. Some manufacturers mentioned that their models mostly undergo wear failures in the field, rather than fracture failures. These wear failures can be attributed to rough terrain and environmental factors that wear down the tires and bearings specifically. To reproduce wear failures, the inclusion of additional test factors in the testing protocol is necessary. Further, the study results also led the manufacturers to comment that the caster test is more rigorous than standard tests as a majority of the casters failed before 100,000 test cycles which is nearly equivalent to 200,000 MDT cycles (representing 3–5 years of outdoor use). The high magnitude shocks on the caster test result from slat impacts are nearer to the centre of the caster compared to MDT; however, these shocks assisted in exposing the weak links in the caster during the study. Failures such as bearing and fork fractures that were witnessed in the field were missed by manufacturers during their standards testing. The high magnitude shocks may be characteristic of outdoor use in LRS which led to representative fracture failures. Still, the feedback about the rigorous nature of the test mandates validation of the test to outdoor shock exposure that can assist in predicting fracture failures more accurately. The ISWP-SWG plans to conduct a series of validation experiments which will be followed with upgrades to the test equipment and testing protocol.

2.5 LIMITATIONS

The caster assembly testing was prioritised and developed as a part of additional wheelchair tests based on consensus from the ISWP-SWG members rather than research evidence, which may cause potential expert bias in this study. The caster assembly testing equipment has been developed for testing against several quality-affecting factors; however, casters in the study were only subjected to load testing. There are certain design shortcomings with the equipment:

(1) The three-wheeler casters have a longer wheelbase and their outdoor behavior such as the bounce they experience after hitting an obstacle cannot be simulated because of space restrictions.

(2) Exposing the caster to quality-degrading factors like corrosion, high temperatures and UV may potentially cause the testing equipment parts to degrade faster but were not used in this study.

(3) Currently, the casters experience a slight bounce after slat impacts as compared to outdoor use. Deploying shock absorbers on the arms can mitigate this.

2.6 FUTURE WORK

The caster test performs durability testing of casters consistently and requires further upgrades for incorporating additional testing factors. The authors plan on validating the shock exposure on caster testing to outdoor shocks by analysing forces and corresponding fatigue experienced by casters in the field and developing different surfaces on the pie-shaped pieces to replicate the effect. This validation will be followed by the addition of more test factors. For integrating corrosion and environmental wear, casters will be subjected to a cascading testing approach. For example, casters can be exposed to humid conditions for corrosion affect followed by UV exposure at an elevated temperature and then conducting accelerated durability testing with slats or other surfaces. It is anticipated that the integration of additional test factors will produce failures that are representative of field failures. The ISWP-SWG plans to integrate the caster test into ISO standards as a new or add-on standard to ISO 7176 or as a technical specification so that they are harmonised with national standards.

3.0 DEVELOPMENT AND PSYCHOMETRIC EVALUATION OF A CASTER FAILURE CHECKLIST

3.1 INTRODUCTION

The global unmet need for wheelchairs is around 95 million and several international organizations including the World Health Organization (WHO), United Nations (UN) and the United States Agency for International Development (USAID) are promoting improved access to high-quality appropriate technology including wheelchairs [1, 5, 13, 14].

In 2006, multiple stakeholders and field experts in the wheelchair sector met in a consensus conference to discuss key issues with wheelchair provision in less-resourced settings (LRS) [18]. The consensus gathered during this conference regarding strategies to address provision issues was compiled to develop the WHO's Guidelines for provision of manual wheelchairs in less-resourced settings (WHO Guidelines) [1]. The second chapter in the WHO Guidelines is provides recommendations to improve the quality of wheelchairs. One of the recommendations is to perform testing of products through standards that are reflective of typical environmental and use conditions in LRS. Based on this recommendation, the International Society of Wheelchair Professionals' Standards Working Group (ISWP-SWG) has focussed on developing appropriate standards since its inception in 2015 [57]. One of the standards prioritised for development is the caster quality testing standard as caster are known to fail frequently with diverse failure modes [13, 112]. To support this claim, the ISWP-SWG experts have collected photographic evidence on caster failures seen in the field. This evidence was presented in Table 5 in the previous chapter. It highlighted the common failure modes seen with caster parts.

Several field trials conducted in LRS have reported failures with casters [47, 53, 82, 86, 88, 89]. In one evaluation study conducted in India, multiple caster problems including missing parts, loss of functionality and part fractures were noted. Failures were noted within 6-months of use [89]. Studies in Kenya to evaluate condition of used wheelchairs have found consistent failures with caster bearings and tires within 1-2 years of use [82, 95]. Field failures of casters are evident in resourced settings as well. One study documented wheelchair incidents in the United States and found that tips and falls out of chairs are significantly associated with the size and design of casters [46]. In addition to field failures, caster failures have been found during durability testing with ISO 7176 standard Section 8 that includes static, impact and fatigue tests [60]. Casters are known to undergo fracture failures throughout such tests [69-80]. Other than part failures, performance issues have been noted with caster as they flutter at high speeds and sink into soft ground causing inconveniences during outdoor travel [18, 89].

To improve caster quality and performance, the ISWP-SWG have made significant progress in developing a caster quality testing standard. New testing equipment was developed in early 2016 which subject casters to accelerated shock testing [112]. Preliminary testing with caster models revealed fracture failures that are common among some of the models. Manufacturers provided feedback on the time to failure for their caster parts. According to the manufacturers, the ISWP caster testing protocol exposes casters to greater shocks than those experienced in the field which causes casters to fail early. This feedback has encouraged reproducing shock exposure on the test equipment to outdoors and addition of suitable test factors so that lab-based testing produces failures as seen in the field. While studies to reproduce outdoor exposure are under progress, the researchers need to rely on anecdotal feedback from manufacturers to compare failures. No data has been available on caster failures except failure photographs. This concern led to a review the tools available in literature and practice that can be utilized for caster failure data collection.

The ISO Wheelchair Testing Standards (ISO 7176) provides a classification for failures seen during durability testing (ISO 7176-8) on multi-drum and cur-drop tests [60]. Wheelchair failures are recorded as Class I, II and III. Class I and Class II failures relate to maintenance issues and can be fixed by user or technician. For example, a loose or missing fastener is a Class I failure and rear wheel tire failures like puncture or wear are classified as Class II. Class III failure are said to occur with structural damage such as frame or caster failures which requires severe repair or part replacement [59]. The purpose behind this failure classification is to inform end of testing. Only two Class I or II failures or one Class III failure are allowed during testing after which testing is terminated. However, this classification does not help with collecting failures from the field in a reliable manner. Failure modes seen in the field cannot be differentiated by this classification system.

Three validated tools are available for data collection on the maintenance state of casters namely, the Wheelchair Maintenance Assessment Tool (W-MAT), Wheelchair Assessment Checklist and Wheelchair Components Questionnaire for Condition (WCQ-C) [50, 113, 114]. Caster evaluation is also a part of the Wheelchair safe and ready checklist in the Wheelchair Service Provision Basic Level Package developed by WHO.[11] All of these tools are developed for evaluating the condition of whole wheelchair and parts. For casters, they instruct the rater to evaluate the caster parts for function and form. Casters are checked for smooth rotation about the stem hub and wheel axle, trueness of the wheel, worn-out tires and missing bolts. Comments can be provided regarding the evaluation. Review of the caster evaluation sections in these tools showed that failures included are not comprehensive. Also, it would be difficult to gage which part is responsible for loss of function. Lack of tools to appropriately characterize caster failures prompted the development of a new tool that can be used by wheelchair technicians, designers, manufacturers, providers and researchers involved in wheelchair testing to report failures.

This study was undertaken to develop a caster failure checklist that includes different caster failure modes through an iterative approach and evaluate its feasibility of use and psychometric properties.

3.2 METHODS

3.2.1 Development

The checklist development began in mid-2016; caster failure modes noted during standardized wheelchair testing studies [69-80], field research trials [47, 53, 82, 86, 88, 89] and those found with photographic evidence collected by ISWP-SWG experts [112] were listed. The failures were separated by caster parts. Part failures commonly seen in the field were selected from the list following consultation with a wheelchair testing engineer with 7 years of testing experience and a technician with over 20 years of experience in wheelchair fitting, maintenance, and repairs. These failures were considered for inclusion in the checklist.

To establish face validity of the checklist, an online Qualtrics survey [115] conducted with the wheelchair expert members of the ISWP-SWG and a clinician providing wheelchairs in resourced settings. The survey included an introduction to the checklist, a description of designs of caster parts and the different failures they encounter. The experts were asked to vote if a caster failure should be included in the checklist and rate the risk of user injury and other wheelchair part failures associated with the caster failure. Experts were also requested to suggest additional failures for including in the checklist. Based on their responses, the checklist was revised to improve face validity.

3.2.2 Test-retest study design

This study was a two cohort repeated measures design to evaluate the test-retest reliability of the caster failure checklist. One cohort rated caster failures with physical evaluation of the casters and the study with participants in this cohort was performed in a university setting. The second cohort included wheelchair technicians, providers, therapists, clinicians and an assistive technology provider from the field who rated caster failures with online evaluation of caster failure photographs. A proposal for conducting this study was submitted to the University of Pittsburgh Institutional Review Board (IRB) which determined that the study design was not considered human subjects related and thus could proceed without IRB approval.

Convenience sampling was followed for recruiting participants in both cohorts. Individuals older than 18 years and have experience working with wheelchairs were qualified to participate in the study. For the physical evaluation group, individuals were approached in person or via email for participation. Participants were informed about the study procedures while recruiting. For the online evaluation group, wheelchair experts in ISWP-SWG and technicians, providers and clinicians affiliated with ISWP were emailed about the study and participation through online surveys. Two weeks of time interval between test and retest was selected based on experiences from test-retest study conducted by the research group earlier [50].

The physical evaluation group was provided a participant code in the study invitation email. Date and time for the two study sessions were requested and scheduled through emails. For both the sessions, the participants were escorted in a quiet study room with a computer and a cart containing casters placed in a sequence according to their numbers. The computer had an online Qualtrics survey [115] opened in an internet browser for study use. Casters were placed in plastic bags with tags having the caster number on them. The participants were informed about the risk of coming in contact with sharp edges and exposure to dust and dirt. Gloves were provided to avoid this risk. A researcher working on this study accompanied the participant in this room to answer any questions they had during the study session. Questions asked were noted.

For online evaluation participants, the online survey link for first survey was sent through the invitation email. They were informed that completing the survey indicated their participation in the study. The second survey link was sent two weeks following the completion date of the first survey.

Casters were numbered randomly for both the groups during the two sessions. For the physical evaluation group, the random number assignment was done using the random number generator in Microsoft Excel 2016 [116]. For the online evaluation group, the survey provided the facility for random caster selection from its repository.

3.2.3 Caster samples

Twenty-eight casters were evaluated by each participant in a randomized order. The checklist contained 14 failure items and each failure was represented at least two times between the 28 samples. The bent fork failure was an exception; only one sample had the failure. Half of the casters were used, failed casters from the field and half were failed casters from laboratory-based wheelchair and caster testing [60, 112]. These failed casters are shown in Appendix C Section C.1.

3.2.4 Power analysis for sample size estimation

Sample size for each cohort was calculated using the procedure for standard error of the reliability coefficient [117]. To assess 28 failed casters, at least 8 participant raters are required in each group to be 95% certain that the reliability is $> 0.8 \pm 0.1$. Assuming dropout of 20%, a sample size of 10 individuals was required in both cohorts.

3.2.5 Survey design

Online surveys were developed in Qualtrics [115] separately for the two cohort. Both surveys introduced the participant to the study procedures and informed them about the different caster parts' design. The participants were presented with different caster failure modes included in the checklist, instructions to evaluate them and their photographic illustrations. A sample checklist with scoring options for each failure was introduced to familiarize the participant with the checklist. The failure items in the checklist were hyperlinks to the evaluation instructions for respective failures. The survey instructed the participants to inspect the casters on the cart one by one and rate the failures using the checklist. A separate comment box was provided at the end of each caster assessment to note down any issues encountered during evaluation. The same survey layout was followed for the two sessions with both the cohorts. For the online group, caster photographs highlighting the failures were embedded in the survey questions.

The first session surveys asked for the participant code (physical evaluation group) or first and last names with email ID (online evaluation group), years of experience with wheelchairs, their occupation and whether they have serviced or repaired wheelchairs. The second session surveys requested participants to rate the easiness of use of the checklist, usefulness of the failure evaluation instructions and illustrations, and willingness to use the checklist in practice to collect failure data. All items were scored individually on a 5-point Likert scale in which 1-do not agree and 5-fully agree. Feedback was requested on the structure and content of the checklist, additional failures for inclusion, suggestions for improvement to the checklist. Participants were asked to comment about their experience with caster failures and the study in general.

3.2.6 Data analysis

With expert review for determining face validity, percentages were calculated for inclusion of the failure item, risk to user consequences and failure risk with other wheelchair parts. Expert comments were reviewed to make improvements to the checklist.

Descriptive statistics were calculated for participant's demographic information. Three response choices were available for rating a failure item – 1) Failure present, 2) Failure not present and 3) Unable to evaluate. They were scored as 1, 2 and 3 respectively for data analysis.

Missing responses were scored as 0. Test-retest and inter-rater reliability for each failure item were calculated using Cohen's Kappa [118] and percentage agreement. Fleiss's kappa was used for interrater reliability estimate as raters were greater than two [119]. Using the algorithm of Landis and Koch[120], kappa values of 0.81 and above represented perfect agreement, values between 0.61 and 0.80 represented substantial agreement, 0.41 to 0.60 represented moderate agreement, 0.21 to 0.4 is fair agreement and values below 0.20 suggested slight to poor agreement. Along with reliability, the accuracy of the responses for each failure mode were calculated. One investigator with experience in caster testing and failure analysis rated the casters using the checklist. The online photographs were rated first followed by physical evaluations. The participant responses for each failure item for each caster were compared to the investigator responses (true scores) for the purpose of determining accuracy. All data analysis was conducted using the statistical package IBM SPSS 24 [121].

3.2.7 Checklist revision

Comments received on each caster feedback from the participants were analyzed to understand the issues participants faced while evaluating casters. Responses received by checklist items with low Kappa agreement scores for both test-retest and interrater reliabilities were reviewed and compared with the investigator responses. This analysis assisted in making further revisions to the checklist, failure modes and their instructions.

Feedback on the revisions was obtained from a wheelchair testing engineer, technician, clinician, an assistive technology provider and two wheelchair manufacturers participating on ISWP-SWG. The checklist was revised based on the expert feedback. Additionally, the checklist was translated into Spanish and reviewed by a native Spanish speaker with a background in rehabilitation science and mechanical engineering.

3.2.8 Preliminary data collection

Preliminary data were collected in Indonesia and Scotland with the revised checklist. Photos and comments were evaluated to understand the cause of failures. These failures were used to compare with testing failures on the caster testing system and is described in detail in Chapter 4.

3.3 RESULTS

The initial list of caster failure modes based on failures found in field studies, wheelchair testing studies and photographic evidence by ISWP-SWG is shown in Table C 1. Fourteen failure modes were considered for inclusion following feedback from the wheelchair testing engineer and technician. Failures selected are presented in Table 10 below.

Table 10. Caster failure modes chosen for checklist inclusion

Caster Part	Failure Mode
Axle bearing	1. Corrosion 2. Obstruction to rolling 3. Fracture
Caster Wheel	1. Fracture 2. Corrosion
Tire	1. Worn-out 2. Tread Worn-out 3. Cracking 4. Deflated
Stem Bearing	1. Corrosion
Stem Bolt	1. Fracture
Fork	1. Bent 2. Fracture 3. Corrosion

3.3.1 Face validity

The survey designed for collecting expert feedback on the failure items for inclusion in the checklist is shown in section C.1. Five experts from ISWP-SWG and a clinician took the online survey. The results of the survey are shown in Table 11. Failures of caster wheel corrosion and tire tread worn-out scored less than 60% for inclusion and are of little to no risk to user consequences and other wheelchair parts. These two items were filtered out.

Table 11. Face Validity Results

Caster Failure Mode	Score for inclusion (%)	Risk for user consequences (%)		Risk for failure of other wheelchair parts (%)	
		Medium Risk – High Risk	No Risk – Low Risk	Medium Risk – High Risk	No Risk – Low Risk
Axle bearing corrosion	100	20	80	20	80
Axle bearing's obstruction to rolling	100	20	80	20	80
Axle bearing fracture	100	60	40	80	20
Caster wheel fracture	100	60	40	80	20
Tire worn out	100	0	100	0	100

Table 11 (continued).

Deflated tire	100	0	100	40	60
Stem bolt fracture	100	100	0	100	0
Bent fork	100	60	40	60	40
Tire cracking	80	20	80	40	60
Stem bearing corrosion	80	40	60	40	60
Fork fracture	80	100	0	100	0
Fork corrosion	80	25	75	25	75
Caster wheel corrosion	60	20	80	40	60
Tire tread worn out	40	0	100	0	100

Four experts recommended one failure mode each for inclusion – 1) Stem Bearing Fracture, 2) Tire Roll-off, 3) Stem and axle bolt not set to specified torque, and 4) Caster Shimmy. The first two items were included as they affect the form and materials of the caster parts. The other two were left out because their evaluations are complex. With most products, there is no torque specification and the tightening is subjective to the technician or supplier. Caster shimmy is a design failure which can cause wheelchair or caster failure and adverse user consequences. Its evaluation can be a part of standard wheelchair or caster testing.

3.3.2 Test-retest study results

In the physical evaluation group, 12 participants completed the test-retest study. All participants had a retest interval of 14 days except one who completed the retest session after 18 days. In the online evaluation group, 26 people were contacted via email for participation. 13 people participated in the first survey and two of them did not rate all the casters. Both of them had insufficient time to complete all the caster evaluations. The other 11 participants completed the both survey sessions and the retest interval in this group was 2.4±0.6 weeks. The demographic characteristics of the participants is shown in Table 12.

Table 12. Demographic characteristics of study participants

Demographic	Physical Evaluation Group	Online Evaluation Group
Experience with wheelchairs (in years)	3.3 ± 2.4	9.4 ± 5.3
Professions (multiple choice response)		
• Engineer	11	5
• Physician	1	2
• Clinician	0	5
• Therapist	0	3
• Designer	3	4
• Manufacturer	0	3
• Technician	1	3
• Other	2 (Researcher)	3 (ATP, Manager, Marketing)
Experience with servicing wheelchairs (Yes/No)	75% Yes, 25% No	100% Yes

The surveys requested for the demographic information at the beginning of the study. The participant was familiarized with different caster parts (see Anatomy of a Caster Assembly in section C.1) and instructions to evaluate different caster failure modes as shown in section C.2. A sample caster failure checklist (see section C.3) was introduced to the participant with the instructions for rating failures with samples using the checklist. Each failure item hyperlinked to its evaluation instructions which opened in a pop-up window. Failures were to be rated as present or not present depending on the evaluation. The option 'Unable to evaluate' was to be selected in case the part could not be evaluated because hand tools were needed to dismantle and assess the part. Participants in both groups were then instructed to rate casters one by one.

The range of test-retest reliabilities found for the checklist items with the physical and online evaluation groups are shown in Table 13 and Table 14 respectively. Percentage of participants falling within each Kappa agreement intervals are shown as well. Reliability scores for each participant are reported in Sections C.4 and C.5. Inter-rater reliabilities and average accuracies for each failure mode are shown in Table 15 and Table 16. The responses provided for feedback questions are included in Table 17 for both groups. The table shows the number of participants that agreed on the statements i.e. Likert scale response greater than 3. Feedback related to online and field use of checklist was not requested from the physical evaluation group. Seventy-five percent participants from the physical group and 55% participants from the online group rated that the checklist was easy to use. The evaluation instructions were helpful to more than 75% participants in both the groups.

Table 13. Test-retest reliabilities for the physical evaluation group

Failure Modes	Range values		Kappa Agreement (% participants)				
	% agreement	Kappa	Poor	Fair	Moderate	Substantial	Perfect
Axle bearing corrosion	71.43-100	0.558-1	0.00	0.00	25.00	0.00	75.00
Axle bearing's obstruction to rolling	50.00-100	0.137-1	16.67	8.33	8.33	50.00	16.67
Axle bearing fracture	32.14-96.43	0.113-0.904	25.00	16.67	8.33	33.33	16.67
Caster wheel fracture	78.57-100	0.453-1	0.00	0.00	8.33	25.00	66.67
Tire roll-off	96.43-100	0.781-1	0.00	0.00	0.00	50.00	50.00
Tire worn out	75.00-96.43	0.462-0.929	0.00	0.00	25.00	50.00	25.00
Tire cracking	75.00-100	0.375-1	0.00	8.33	25.00	16.67	50.00
Deflated tire	67.86-100	0.242-1	0.00	8.33	16.67	33.33	41.67
Stem bearing fracture	50.00-92.86	0.25-0.881	0.00	16.67	16.67	50.00	16.67
Stem bearing corrosion	67.86-100	0.481-1	0.00	0.00	16.67	25.00	58.33
Stem bolt fracture	71.43-96.43	0.517-0.939	0.00	0.00	8.33	25.00	66.67
Bent fork	85.71-100	0.724-1	0.00	0.00	0.00	25.00	66.67
Fork fracture	82.14-100	0.52-1	0.00	0.00	8.33	8.33	83.33
Fork corrosion	78.57-100	0.674-1	0.00	0.00	0.00	16.67	83.33

Table 14. Test-retest reliabilities for the online evaluation group

Failure Modes	Range values		Kappa Agreement (% participants)				
	% agreement	Kappa	Poor	Fair	Moderate	Substantial	Perfect
Axle bearing corrosion	53.57-96.43	0.37-0.93	0.00	9.09	9.09	54.55	27.27
Axle bearing's obstruction to rolling	39.29-92.86	0.14-0.87	9.09	45.45	18.18	18.18	9.09
Axle bearing fracture	25.00-92.86	0.12-0.68	54.55	18.18	18.18	9.09	0.00
Caster wheel fracture	50.00-100	0-1	9.09	27.27	36.36	9.09	18.18
Tire roll-off	78.57-100	0.39-1	0.00	9.09	18.18	36.36	36.36
Tire worn out	67.86-92.86	0.14-0.76	9.09	18.18	18.18	54.55	0.00
Tire cracking	67.86-96.43	0.35-0.86	0.00	9.09	54.55	18.18	18.18
Deflated tire	78.57-100	0.45-1	0.00	0.00	9.09	45.45	45.45
Stem bearing fracture	53.57-96.43	0.01-0.76	27.27	18.18	18.18	36.36	0.00

Table 14 (continued).

Stem bearing corrosion	64.29-92.86	0.30-1	0.00	27.27	9.09	45.45	18.18
Stem bolt fracture	42.86-100	0.15-1	9.09	9.09	18.18	45.45	18.18
Bent fork	35.71-100	0.04-0.93	18.18	27.27	18.18	0.00	18.18
Fork fracture	42.86-100	0.18-1	9.09	0.00	36.36	18.18	36.36
Fork corrosion	42.86-96.43	0.29-0.94	0.00	18.18	18.18	9.09	54.55

Table 15. Interrater reliabilities for the test and retest sessions of the physical evaluation group

	Test session			**Retest session**		
Failure Modes	**Kappa**	**%agreement**	**Accuracy (%)**	**Kappa**	**%agreement**	**Accuracy (%)**
Axle bearing corrosion	0.712 ± 0.019	89.29	77.38 ±5.12	0.708 ± 0.019	89.88	78.87 ± 4.24
Axle bearing's obstruction to rolling	0.367 ± 0.018	82.14	62.80 ± 11.24	0.406 ± 0.019	80.36	60.12 ± 9.65
Axle bearing fracture	0.182 ± 0.018	74.70	66.67 ± 15.73	0.386 ± 0.018	84.23	72.32 ± 10.83
Caster wheel fracture	0.831 ± 0.022	98.21	98.21 ± 2.73	0.775 ± 0.021	97.02	97.02 ± 5.02
Tire roll-off	0.802 ± 0.022	97.62	97.02 ± 1.97	0.887 ± 0.023	98.81	98.81 ± 1.68
Tire worn out	0.438 ± 0.024	83.33	77.38 ± 10.94	0.381 ± 0.023	81.25	77.98 ± 14.49
Tire cracking	0.617 ± 0.023	89.88	89.29 ± 6.36	0.56 ± 0.024	89.58	89.58 ± 6.59
Deflated tire	0.305 ± 0.019	91.67	91.67 ± 12.90	0.511 ± 0.022	94.35	94.35 ± 10.9
Stem bearing fracture	0.485 ± 0.017	77.08	73.21 ± 13.95	0.542 ± 0.017	80.06	74.70 ± 12.67
Stem bearing corrosion	0.693 ± 0.017	86.61	85.42 ± 13.24	0.715 ± 0.017	88.99	86.31 ± 12.86
Stem bolt fracture	0.665 ± 0.018	89.29	87.50 ± 9.73	0.726 ± 0.018	91.07	90.18 ± 9.57
Bent fork	0.77 ± 0.022	93.15	93.15 ± 10.25	0.75 ± 0.021	93.45	93.45 ± 10.60
Fork fracture	0.771 ± 0.019	92.86	92.86 ± 10.31	0.817 ± 0.019	93.15	93.15 ± 9.16
Fork corrosion	0.758 ± 0.017	90.77	90.77 ± 9.83	0.811 ± 0.018	91.96	91.96 ± 9.00

Table 16. Interrater reliabilities for the test and retest sessions of the online evaluation group

	Test session			Retest session		
Failure Modes	**Kappa**	**%agreement**	**Accuracy (%)**	**Kappa**	**%agreement**	**Accuracy (%)**
Axle bearing corrosion	0.393 ± 0.019	69.48	60.71 ± 21.80	0.412 ± 0.019	80.71	51.30 ± 19.93
Axle bearing's obstruction to rolling	0.188 ± 0.021	60.71	43.18 ± 26.79	0.152 ± 0.021	69.29	29.55 ± 24.37
Axle bearing fracture	0.081 ± 0.018	58.77	50.97 ± 23.20	0.042 ± 0.023	66.23	40.91 ± 23.76
Caster wheel fracture	0.356 ± 0.021	84.09	79.55 ± 4.84	0.564 ± 0.021	90.58	85.39 ± 7.98
Tire roll-off	0.479 ± 0.022	94.81	94.81 ± 7.20	0.742 ± 0.024	96.10	96.10 ± 5.15
Tire worn out	0.209 ± 0.023	76.62	74.68 ± 22.40	0.381 ± 0.026	81.82	79.22 ± 15.96
Tire cracking	0.448 ± 0.022	84.09	84.09 ± 9.06	0.454 ± 0.024	88.31	88.31 ± 8.76
Deflated tire	0.677 ± 0.022	96.10	96.10 ± 3.87	0.953 ± 0.027	98.05	98.05 ± 3.18
Stem bearing fracture	0.131 ± 0.023	65.91	62.34 ± 16.43	0.193 ± 0.022	64.94	60.71 ± 21.10
Stem bearing corrosion	0.251 ± 0.2	67.21	62.34 ± 18.78	0.335 ± 0.022	67.86	62.34 ± 24.57
Stem bolt fracture	0.189 ± 0.024	69.81	69.16 ± 14.94	0.403 ± 0.022	73.38	71.43 ± 17.50
Bent fork	0.186 ± 0.026	67.86	67.86 ± 18.71	0.416 ± 0.025	82.79	79.87 ± 15.48
Fork fracture	0.341 ± 0.022	72.73	72.73 ± 14.94	0.575 ± 0.021	84.42	84.42 ± 14.06
Fork corrosion	0.409 ± 0.02	76.95	75.00 ± 13.54	0.594 ± 0.19	80.84	77.27 ± 16.84

Table 17. Feedback by study participants on the use of checklist and related materials

Statements for checklist feedback	**Physical evaluation group (n=12)**	**Online evaluation group (n=11)**
The caster anatomy information was redundant in this survey	0	6
The instructions for evaluating casters were helpful	8	9
I need more training materials before using the checklist	1	1
The checklist is easy to use for rating caster failures	8	6
Evaluating the casters through photos was difficult	NA	5
I would like to use the checklist for collecting failure data on casters	NA	3
I prefer using the checklist online through a laptop, phone or tablet for collecting failures	NA	7
I prefer using a paper version of the checklist for collecting failures	NA	2

Participants provided constructive feedback for improving the checklist. Some of them from the physical evaluation group suggested provision of additional example photos for failure modes and inspection videos. Few of them advised providing information on what degree of failure (such as those related to corrosion and obstruction to rolling) qualifies as failure. Four participants recommended adding another rating option of ‘Part not available for evaluation’. Participants that were not familiar with caster designs suggested adding photos of functional casters for comparison with failed casters. Online group participants recommended taking clear pictures of failed casters (with proper focus and brightness) and adding more than one view to simplify evaluation of all parts. One expert suggested adding more information on evaluation of bearing seals.

Suggestions for additional failures included corrosion failures for fasteners, stem bolt, and stem bearings, tread worn-out, loose fasteners and missing parts. Mixed responses were received regarding using the checklist and the conduct of the study. In the physical evaluation group, one participant noted that the checklist is useful with correct training experience. Two participants in the same group said that the checklist is intuitive and easy to follow. Two participants were dissatisfied; one with plastic bags becoming dirty and the other with the arrangement of casters on the cart. Two participants expressed that the tire wear and rolling obstruction failures are subjective and appropriate evaluation information should be provided.

3.3.3 Checklist revision

Evaluation of individual responses highlighted the causes for low reliability scores. Table 18 shows the evaluation results and the revisions made to the checklist to eliminate discrepancies with evaluation.

Table 18. Assessment of individual responses for physical and online caster evaluations

Evaluation issue	Revision to the checklist
1. One of the most important factor affecting reliability and accuracy scores of all failure items is the confusion with rating for missing parts. Participants were not sure which option to choose between 'Failure not present' and 'Unable to evaluate'.	1. Rating choices and evaluation instructions were updated. Missing parts was added as an option. Evaluation instructions were updated for all parts and detailed evaluation was requested wherever necessary.
2. In many cases, bearings were not visible and so, the participants guessed the failure based on condition of the caster. For instance, some participants rated bearing failure when the only part that has a fracture failure is the fork. In one case, there were no bearings on the caster and three participants rated it for corrosion failure since the caster was corroded.	The evaluation instructions were updated to evaluate the bearings in detail. It was noted in the general evaluation instructions that the participant should not guess the failure based on condition and rate a failure if the evaluation is not completed based on the instructions. In bearing evaluation instructions, it was noted that the participant should rate 'Unable to evaluate' if the detailed evaluation is not carried out.
3. Participants thought that loose washers are part of the bearings and scored it as a fracture failure. In some cases, failed bearings were left in the bags and not evaluated at all.	The instructional materials note that the participant should go through the information on caster designs and parts before checking the evaluation instructions.
4. Broken seals were not scored as failures.	Instructions were updated to note seal failures as bearing fracture failure. For seal damage, the participant is requested to add seal damage as the failure in the comment box. Failure examples were shown through photos.
5. Failures of tire worn-out and cracking were found to be confusing. Some participants rated tread wear as tire worn-out.	Instructions for tire failures were described in detail to explain differences in tire worn-out, tread worn-out and cracking. Tread lost failure was added.
6. Any dirt on the tire was rated as tire wear	It was noted in instructions that dirt on tire should not account for wear.
7. When inspecting for tire deflated failure, several participants did not check if the tire was pneumatic. Accuracy is higher with this failure but not reliability because it is rated for no failure plenty of times correctly i.e. true negatives are higher.	Instructions were added for checking the pneumatic tire by looking for a valve prior to rating the failure. Photos were provided as examples.

Table 18 (continued).

8. Corrosion and obstruction to rolling failures were found to be subjective. Participants were ambiguous about what degree of corrosion and obstruction should be rated as failure.	Corrosion was divided into mild and high corrosion as the failure modes. Both failure modes were distinguished based on the outcomes of the evaluation. Instructions for evaluation of bearing corrosion were added. The obstruction to rolling failure was changed to sticky bearing failure for axle bearings. Examples of sticky bearing evaluation was provided through GIF images.
9. Online participants were restricted to visual analysis. Most failures needed physical inspections and they were inconsistently rated.	Visual evaluations were found to be not reliable and revisions for online caster evaluations were not pursued.

Analysis of individual responses and feedback provided by the study participants led to improvements in checklist structure, addition of appropriate failures and development of an online portal on WordPress platform[3] containing information regarding checklist use, caster designs, different types of caster parts and failure evaluations. Failure of missing fasteners were added to the checklist as well. The unable to evaluate option was made available for bearings and the stem hub assembly parts only. Based on evaluation of field samples used in the study, failures of axle bearing contamination, bent stem bolt, locked stem bearings and loose fork were added.

The revised checklist and materials on the information portal were evaluated by experts who recommended designing the checklist survey for evaluating parts in a sequence such that the activity takes minimum time. For the same, suggestions were provided on the survey structure for quick evaluation. Response choices for a few failure modes were updated. The checklist was revised based on feedback. Items in the revised checklist are – 1) Tire failures: missing tire, roll-off, deflation, worn-out, lost tread, and cracking; 2) Wheel failures: missing wheel and fracture; 3) Fork failures: missing fork, fracture, bent, loose, mild corrosion and heavy corrosion; 4) Stem bolt failures: missing bolt, fracture, bent, mild corrosion and heavy corrosion; 5) Axle bearing failures: missing bearing, sticky, fracture, mild corrosion, heavy corrosion, and contamination; 6) Stem bearing failure: missing bearing, loose, locking, fracture, mild corrosion and heavy corrosion; and 7) Fastener failures: missing fasteners. The 'Unable to evaluate' response choice was provided for stem bolt, bearings, and fasteners. The Spanish version of the checklist materials was developed for collecting failure data from Spanish speaking countries.

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[3] https://wordpress.com/

The revised checklist survey and the Spanish checklist survey are shown in Sections C.6 and C.7 respectively. They are available online through the Qualtrics service[4,5]. The checklist and the related informational materials were published online[6] and disseminated through email and ISWP newsletter to several ISWP partners and subscribers for collecting data on caster failures seen in the field.

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[4] https://pitt.co1.qualtrics.com/jfe/form/SV_3epYmwLWbQjjxpH

[5] https:/pitt.co1.qualtrics.com/jfe/form/SV_8fgBEfkENh1sgFn

[6] https://casterchecklist.wordpress.com/

3.3.4 Preliminary failure data collected through the checklist

Two users of the checklist at repair facilities in Indonesia and Scotland submitted 24 failed casters through the revised checklist. Figure 14 shows the frequency of failure modes seen with different caster models. Figure 15 and Figure 16 show failure photos submitted with these evaluations.

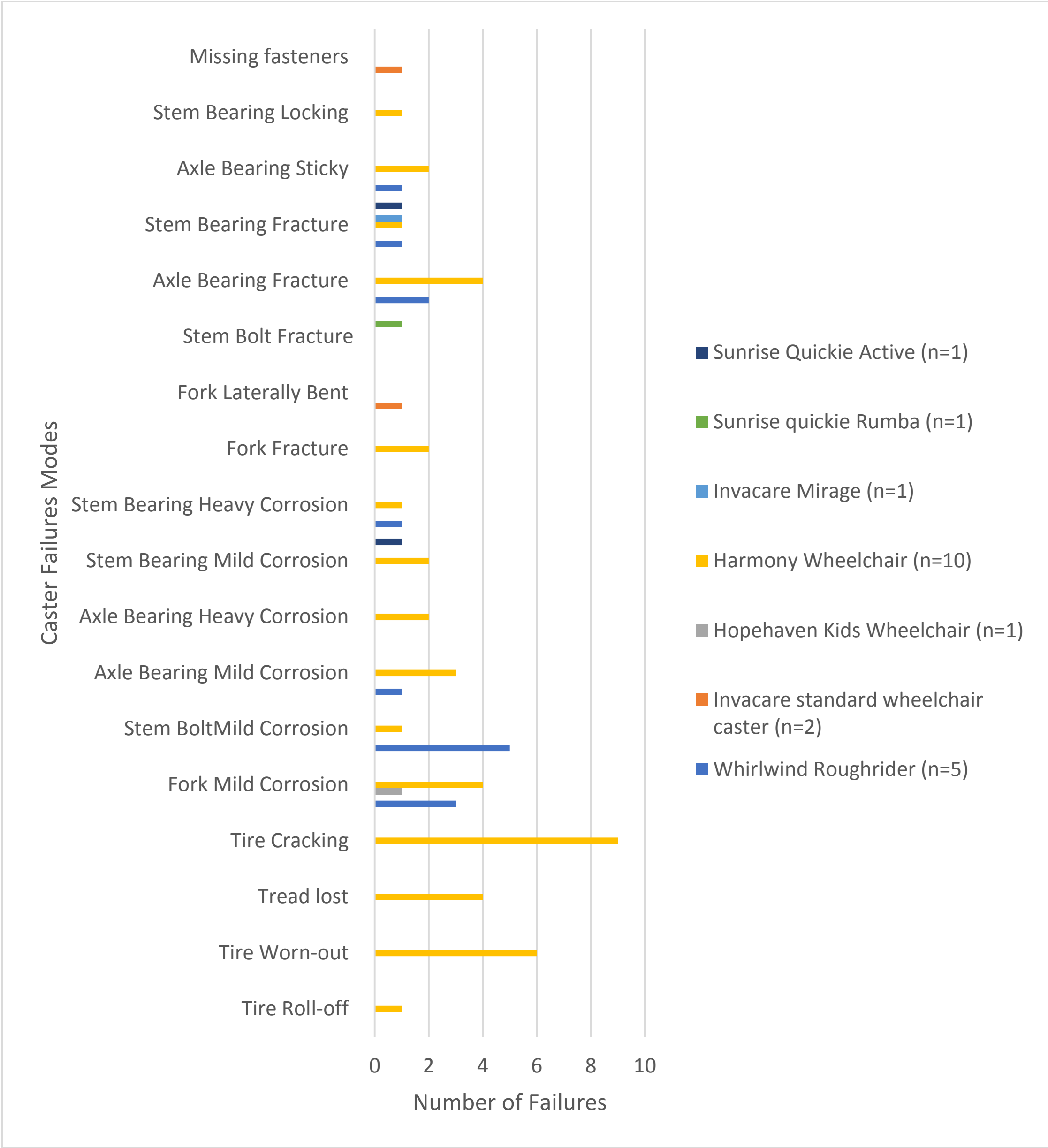

Figure 14. Field failures collected using caster failure checklist

Figure 15. Caster failures with Harmony wheelchairs.

Figure 16. Caster failures with Whirlwind Roughrider (left), Sunrise Quickie Rumba (center) and Invacare Mirage (right)

3.4 DISCUSSION

Lack of standard tools to collect data on caster failures seen in the field motivated the development of the caster failure checklist. This study describes the iterative approach used by the authors in developing the checklist. Feedback from wheelchair experts and participants in the test-retest reliability testing study which included wheelchair manufacturers, designer, providers, clinicians, researchers, and rehabilitation professionals was used to improve the checklist at various stages of development.

Face validity of the checklist was evaluated to check whether the caster parts and their respective failure modes included in the checklist are comprehensive and relevant to the domain of caster failures seen outdoors. This validity was assessed through a survey questionnaire. Expert feedback regarding inclusion of failures and assessment of their risk to users and failure of other parts was valuable. Fourteen failure modes commonly seen with different caster parts in the field were considered appropriate for inclusion and the checklist was further evaluated for reliability.

The test-retest reliability study received a favorable response for participation with the online evaluation group having a suitable mix of people from different professional backgrounds with sufficient experience in wheelchairs. Participants in this group could be considered as target users of the checklist. Although two participants were not available for the second online survey session, the number of raters were sufficient to provide statistical power to this study. In addition to percent agreement, Kappa was used as a measure of reliability since percent agreement does not correct for agreement due to chance and overestimates reliability. This is also evident in the study results. Caster evaluated in the study by both groups had significant variability in their designs and failures which is important for reliability evaluation.

Test-retest reliability scores for the checklist items were higher for physical evaluation group compared to online evaluation group. The percent agreement and range for the reliability estimates were provided in the results since intra-rater reliability (test-retest reliability in this case) cannot be averaged. About 75% participants or more had substantial to almost perfect test-retest reliability for 10 failure modes in the physical evaluation group. And, 50-66.67% participants had the substantial to almost perfect reliability for the other four failures of axle bearing fracture, axle bearing's obstruction to rolling, tire cracking and stem bearing fracture. For these four failures, interrater reliability was found have poor to fair agreement. Tire worn-out and deflated tire were two other items that had fair rater agreements. Accuracy was found to be greater than 75% except for two axle bearing failures. These favorable results indicate that the checklist is a valid tool for collecting data on caster failures when casters are evaluated physically.

The online failure evaluation group struggled with caster evaluations through photographs which is evident in the study results. Only 2 out of 14 failures had substantial to almost perfect test-retest and interrater reliability scores. The accuracies for the evaluations are moderate with significant variance. The two failure modes that received favorable scores were visible clearly in the photographs which assisted participants in rating them correctly over time compared to others. Issues seen with the physical evaluation group were also noted with the online group. Most participants predicted failures in case the part (like bearings) was not visible in the photograph. While the photographs attempted to highlight failures, loss of focus and less brightness on other parts led to loss of information which left participants guessing failures based on caster condition. Some part failures such as bent fork required two views which were not provided which led to unreliable responses. Evaluations such as obstruction to rolling were rated as failures when they are only possible with physical inspections. Like the other group, the online group was confused with rating for missing parts. Participants commented regarding the level of corrosion for some casters which may or may not qualify as failure. Such discrepancies and unfavorable testing results informed that online caster evaluation is not a reliable method for collecting caster failures.

Feedback regarding usability of the checklist was positive from both study cohorts. Participants appreciated the training provided through introduction to caster designs, parts and their failure modes. The failure instructions were helpful for the participants during evaluations. The checklist was easy to use and a few participants affirmed this usability aspect through their feedback comments. Online participants rated that evaluation through photographs was not difficult however their comments for each caster evaluation does not comply with their rating for photographic evaluation. Technicians, rehabilitation professionals and clinicians in the online group expressed interest in using the checklist. Online survey on laptop or mobile was the chosen medium for data collection rather than doing manual entries on paper. Based on this feedback, study findings and suggestions for improvement, the authors upgraded the checklist and related materials to make the failure evaluations consistent and the checklist reliable for use.

New failure modes were added and some of them were renamed and classified further. The caster informational materials were revised significantly. Failures were described in greater detail, many failure examples (pictures in JPEG and GIF formats) were included and the caster failure evaluation instructions were explained in depth. The revised checklist has a simple look and is estimated to take less than five minutes for a caster failure evaluation. It requests for wheelchair brand, age in months, location of use and two photos of caster failures that will be reported. The checklist is divided into parts which can be evaluated sequentially. Hyperlinks associated with all failure modes are linked to a website which provides quick access to detailed evaluation instructions with examples. The checklist and its materials can be accessed through browsers on typical smartphones with Android and iOS. Another round of evaluation of the upgraded checklist and materials by experts was crucial prior to dissemination. Their suggestions led the authors to revamp the checklist structure for easy use and quick caster evaluation in the field. A paper version of the checklist was developed to allow manual data collection in less-resourced settings where internet connectivity is limited. This version was evaluated by the experts too. The iterative feedback approach employed in this study had led to development of a valid and standardized tool and materials.

The checklist, including the Spanish version and the paper version, were disseminated for caster failure data collection. Preliminary data collected provides comprehensive details on caster failures. Tire and bearing failures are notable with certain models. Few fracture failures are seen with standard and power wheelchairs. Comments received with the caster evaluations highlight the cause for failures. The standard and power wheelchairs suffered fracture failures due to impacts. The Whirlwind caster has issues with axle bearing performance because of yarn and hair that get in between the bearing and the fork. Photos provided with the evaluation are helpful as well. Some of them indicate the wearing experienced by casters outdoors due to environmental conditions. Modifications made to the casters to survive longer are also evident. Further data collection on caster failures is anticipated from multiple locations in LRS which can help in characterizing the failures better and make reliable comparison with the in-lab testing failures.

3.5 LIMITATIONS

The study has several limitations as below –

1. Experts and participants involved in the study were a convenience sample and not randomly selected. Many experts were affiliated with ISWP-SWG which is interested in improving caster design and durability, and this could have led to their favorable feedback. Participants from the physical evaluation group were engineers and researchers from a university setting and were not representative of the target users of the checklist like the online evaluation group.
2. Presence of the investigator in the study room may have influenced the participant's behavior, ability and responses during the physical evaluation study session.
3. There may have been some learning effect which is typical of test-retest studies.
4. The revised checklist and related materials on the website developed after the test-retest study and expert feedback was not tested prior to dissemination. Most of the checklist items were tested as a part of the study but the new failure modes were not.
5. There was no structured survey pretesting conducted prior to the test-retest reliability study which may have improved the reliability scores found with this study.
6. The number of samples reported through the checklist is small to synthesize common failure modes for the seven models. Additionally, there is greater variability seen in the parts quality, especially in LRS and no information about how often the wheelchair is used. These limitations make it difficult to reach definite conclusions about caster failures.

3.6 FUTURE WORK

The caster failure data to be collected through the standardized tool can be used to compare failures found in different settings. Technicians can use it while servicing the wheelchair to report field failures. Manufacturers and international wheelchair testing laboratories can rate failures found during quality testing using ISO 7176 wheelchair tests. The researchers involved in ISWP-SWG plan to compare the field failure data with the results from the ISWP caster testing [112]. It is estimated that the field data on different models can inform the testing protocol in many ways. A database of caster failures will be developed soon which will contain field and lab-based failures collected through the checklist. Correlating failures in different settings and conducting failure analysis can assist in improving designs for optimal reliability. Additionally, failure data collected through the checklist can be analyzed to assess the generalizability of the checklist in different settings.

4.0 DEVELOPMENT OF CASTER TESTING PROTOCOL BASED ON FIELD EXPOSURE

4.1 INTRODUCTION

Wheelchair durability is a concerning issue in less-resourced settings (LRS). There are a couple of reasons why this issue exits. Firstly, designs provided are inappropriate and of poor quality [17, 18, 21-24, 26, 27]. Secondly, the environmental conditions in LRS are different than those experienced in resourced settings which impose greater durability requirements on wheelchair products. Wheelchairs users have to maneuver through rocky and rough terrains, muddy roads, gravel, sand, and potholes [1, 18, 22, 23, 26, 42-44]. And since most LRS fall in the tropical zones [93], varying seasonal conditions, elevated temperatures and high humidity are common [1] that causes products to wear down quickly. Thirdly, users in LRS use wheelchairs for multiple purposes than just mobility which adds to the demand for greater strength and wear resistance. Lastly, lack of access to rehabilitation services, tools and skilled labor makes servicing and maintaining wheelchairs difficult. These factors together affect wheelchair durability resulting in frequent failures and breakdowns. That makes wheelchairs unreliable for use and can impact the user economically and socially.

Field studies have found several quality discrepancies with wheelchair parts. In a recent study [95] evaluating condition of four wheelchair models used in LRS over a period of two years, brakes, seats, casters, footrests, cushions, tires and frames were found to be wear down significantly or broken. Bearings were found to be loose or fractured. Missing parts was a common issue. Similar part failures, repairs, replacements and missing parts have been reported in other field studies over 2 weeks to 8 months of field use [29, 47, 53, 83, 88, 89]. In one study, more than 75% of users (n=94) were found to be dissatisfied with the durability and weight of unsuitable products that were provided in Zimbabwe [27]. Anecdotal reports state that donated wheelchairs often last no more than three to six months [17, 18, 22]. The WHO Guidelines on provision of manual wheelchairs in less-resourced settings (WHO Guidelines) recognize these product quality issues prevalent in LRS and recommend testing of wheelchairs [1].

WHO Guidelines refer to wheelchair standards (ISO-7176) published by the International Organization for Standardization (ISO) for product testing [60]. These standards include tests for stability, durability, performance and dimensional measurements. Durability tests include fatigue tests that require a wheelchair to pass 200,000 test cycles on a multi-drum test (MDT) and 6,667 cycles on a curb drop test (CDT). Passing these tests is representative of 3-5 years of outdoor use [59, 67]. Standards testing has been conducted for more than 20 years in wheelchair testing laboratories. Results from these testing studies indicated failures with wheelchairs already on the market, premature failures with wheelchair produced in LRS and no significant improvement in wheelchair quality over the years [69-80]. Moreover, the fatigue testing procedures have remained consistent [78] since publication in the 1990's and there is no published evidence supporting the validity of the standard testing methods.

One research study compared outdoor wheelchair exposure to the ISO fatigue tests. VanSickle et al. studied the effect of realistic road loads on wheelchair user's comfort and found dissimilarities in the actual use of wheelchairs in outdoor environments and the shock exposure they receive on MDT and CDT [122]. He found wheelchair users rolling over obstacles or curbs rather than falling off which is simulated in the CDT. Forces evident with MDT and CDT were found to be greater compared to field use. The researcher advised reviewing the ISO tests based on outdoor exposure and failure modes. Alterations to the MDT and CDT testing equipment and protocol were suggested. Another suggestion in the study was development of a new testing protocol to simulate field exposure. A similar recommendation for testing validation has been outlined in the WHO Guidelines. The guidelines state that standard testing methods simulate the urban environments witnessed in resourced settings and to replicate the adverse conditions in LRS and rural areas, additional standards are needed that simulate those conditions [1]. Findings from a recent literature review investigating the additional wheelchair standards needed for LRS reciprocated the same view [13]. Based on the reviewed studies from RS and LRS, ISO test qualification may be representative of 3–5 years of outdoor use for RS but apparently falls short of qualifying products for adverse conditions seen in LRS and rural areas of RS. Accurate prediction of life duration of certain wheelchair parts may not be guaranteed.

Researchers and wheelchair experts from the International Society of Wheelchair Professionals' Standards Working Group (ISWP-SWG) resonate with the need for additional standards and validated test methods stated in the WHO Guidelines. The group evaluated the differences in conditions in LRS and those simulated with standards testing. The outcome was the development of a product testing matrix which informed the development of additional tests recommended by the WHO Guidelines (see Table 4). The group prioritized caster testing for development and built a testing equipment (see Figure 9) through an iterative design and expert review approach [112]. Casters are suspended from arms of suitable length on a turntable that can rotate in both directions. The testing conditions were benchmarked to MDT; two slats of half inch thickness similar to those on the MDT were employed for shock exposure. Preliminary testing with a variety of caster models was conducted. Comparison of the resulting failures with anecdotal reports of outdoor failures from manufacturers indicated the need for additional factors and validation of testing factors. Inclusion of corrosion and abrasion as environmental testing factors was recommended based on the nature of failures seen with the models in LRS.

In an effort to develop a validated caster testing protocol, this study had a twofold purpose: 1) validation of different testing factors – shock, corrosion and abrasion and investigating the effect of each factor on caster durability through caster testing of different models and 2) comparison of caster test failures with field failures.

4.2 METHODS

Validation of shock and environmental factors of corrosion and abrasion to corresponding field exposures was conducted through different approaches.

4.2.1 Determining shock exposure based on field conditions

The approach for shock validation involved collecting accelerations experienced by casters outdoors in LRS and simulating the same acceleration pattern on the caster test. Acceleration data was recorded with four wheelchair users in Kenya using wheelchair models commonly used in LRS. This data collection was conducted by researchers from Letourneau University and data was transferred to University of Pittsburgh through a data transfer agreement. The study was reviewed and approved by the Institutional Review Board of Letourneau University.

Acceleration data was recorded using the same instrumentation on the caster test frame, caster test arms and forks of the caster models of wheelchairs on which data was recorded in Kenya. Shock exposure on the caster test was simulated using slats or bumps of different thicknesses. Due to limited availability of casters, only two caster samples of each model were used for this purpose.

Acceleration data from the two settings was analyzed in two ways. First, the data was converted from raw value to acceleration values in terms of g units which is acceleration due to gravity. For data collected on caster test, the time domain data was translated to frequency domain using the Fast Fourier Transform (FFT). Power spectral densities (PSD) were computed and compared to evaluate whether the frequency ranges having greater energy content in the field were amplified on the caster test. Frequency analysis was carried out in MATLAB [123]. The second approach used was comparison of field and lab data using histogram correlation. Bending stress analysis was performed to determine the range of accelerations that cause fatigue for the particular caster models. Accelerations were binned appropriately into bins of 1g interval and the resulting histograms of accelerations from field and caster test were compared. Chi-squared test was used to evaluate the goodness of fit between the histograms.

4.2.2 Determining corrosion exposure based on outdoor corrosion rates

The product testing matrix (Table 4) developed by the ISWP-SWG experts includes several failures caused by corrosion. The ISO-7176 testing methods include testing wheelchairs in hot and cold environments however, it does not simulate salt and humidity exposure which are responsible for corrosion. Hence, based on a consensus vote, corrosion evaluation of the complete wheelchair and wheelchair parts was recommended based on established standards like

ASTM B117 [92]. The standard includes the apparatus and operational conditions for corrosion testing. ISWP procured a salt fog testing chamber specified in this standard which is installed and operational at University of Pittsburgh. The test conducts accelerated corrosion of metals. Corrosion for caster assemblies was to be conducted in the corrosion chamber and validation was necessary to correlate outdoor corrosion to corrosion seen in the salt fog.

Online searches were conducted simultaneously to gather data on field corrosion and corrosion evaluation methods. Outdoor steel corrosion rates reported in different parts of the world were collected by searching literature and online reports on Google Scholar. Keywords used for searching titles in alphabetical order were: corrosion + outdoor, evaluation and rate. Only the corrosion rates reported in terms of millimeters/year or micrometers/year units were collected. Methods to evaluate corrosion rate in the salt fog were found through an online search for corrosion evaluation standards published by ISO and American Society of Testing and Materials (ASTM). Standards relevant to paint and coatings were reviewed for procedures and formulae to evaluate corrosion. An experiment with mass loss test panels was performed to determine the amount of corrosion seen in the salt fog over time. Based on the results, corrosion rate was calculated and correlated with outdoor corrosion rates.

4.2.3 Determining abrasion exposure based on tire wear seen outdoors

Caster tire failures such cracking or being worn-out are caused by abrasion that occurs when tires scrub and roll on rough surfaces with gravel, sand and stones. To identify the rate of abrasion that happens in LRS, failed casters of three different models were collected from Kenya. Period of caster use was recorded in months. Difference between outer diameters of the used and unused casters was measured at three different points on the tire to compute the yearly wear seen by the models.

Simulation of the rough surface on the caster test was done by using sandpaper. Two different grit sizes were evaluated with slat pattern found with the validation approach. Sandpaper with suitable grit was selected for further caster testing.

4.2.4 Validated caster testing conditions

Casters of different models were tested through four distinct conditions with validated testing factors – 1) shock testing; 2) corrosion + shock testing 3) abrasion + shock testing and 4) corrosion + abrasion + shock testing. Two samples of each model were tested through each testing condition. Due to unavailability of samples, some models were not tested through all the four conditions. In the first condition, samples were subjected to shocks caused by slats on the caster test. The second condition exposed casters to corrosion in the salt fog chamber for a certain number of hours and later, they were subjected to shock exposure as in the first condition. In the third condition, casters are subjected to wear by sandpaper attached on the caster test turntable along with slats on top. Casters were tested until fracture failures with metallic parts, tire failures like severe cracking and delamination, and plastic deformation such as bent parts. Functional failures with parts as found during the course of testing were noted. To determine whether corrosion and abrasion have significant effect on caster durability, single factor ANOVA was conducted for each model between the four testing conditions with a 0.05 level of significance. The caster failure checklist was used to rate all failures found with the caster models.

4.2.5 Aggregating field failures and comparing with testing failures

Field failure data on casters was collected in two ways. First, the validated version of the caster failure checklist (developed in Chapter 3.0) was used to rate caster failures at wheelchair service facilities in Indonesia and Scotland. Failures with some standard model samples collected from Scotland were rated in person by the investigator. Second, wheelchair evaluations were conducted in Kenya using another validated tool – Wheelchair Components Questionnaire for Condition (WCQ-C) [114] and the raters commented on caster failures. These comments were analyzed and reported failures were categorized into failure modes in the caster failure checklist. Frequencies and percentages of the field failure modes were calculated, and the three leading failure modes observed with the models in the field were compared with failure modes found with caster testing. Caster failure modes with the highest risk for user injuries (based on expert feedback in Chapter 3.0) were compared as well.

4.3 RESULTS

4.3.1 Shock validation results

4.3.1.1 Instrumentation

Field data were collected with three wheelchair models of Motivation Rough Terrain Wheelchair (MRT), Whirlwind Roughrider (WRR) and Hopehaven Kids Wheelchair (HKC) shown in Figure 17. Two users of HKC, and one user each of MRT and WRR participated in the data collection study. The users were from a boarding school setting in a hilly, high altitude area with uneven terrain and streets without pavements. Accelerometer model X16-1D [124] with 3-axis ±16g capability was employed for recording acceleration data on casters. The sampling rate used was 400Hz and is suitable to prevent aliasing. The sensor was packed in a black box containing two D-size batteries to provide power for a week's time of data collection. As shown in Figure 18, the box was attached to wheelchair frames just above the casters using duct clamps.

Figure 17. MRT (left), WRR (center) and HKC (right)[95]

Figure 18. Accelerometers on MRT (left), WRR (center) and HKC (right) wheelchairs

Figure 19. Accelerometers installed on MRT (left), WRR (center) and HKC (right) casters

On the caster test, accelerometers were bolted/tie-wrapped directly to the caster fork as shown in Figure 19. A bubble level was used to verify the orientation of the accelerometers. Shocks seen with slats of quarter, half and three-quarter inches at four speeds of 0.5m/s, 0.75m/s, 1m/s and 1.25m/s were recorded. Casters were loaded with 20lbs (half of maximum weight on the casters) as the field data was collected with pediatric participants. Initial testing and data recording with the MRT caster showed that it required higher size slats of one to one-quarter inch thickness to reproduce accelerations it sees in the field. Prolonged high amplitude shock testing was risky for the system because the shocks caused the caster arm and test equipment to vibrate significantly. Considering the risk, the MRT caster was omitted from further analysis and testing.

4.3.1.2 Frequency domain analysis

A few events evident during caster testing were observed in the FFT’s generated for accelerations collected on the caster test frame, arm and caster fork of WRR (See Appendix D) with a maximum plotting frequency of 200Hz. Slat hits to the caster that impart vibrations to the equipment were evident. Caster bounce after hitting slats was present in the FFT. Other than that, it was difficult to pinpoint any prominent frequencies as the data contained significant noise. PSDs as shown in Figure 20 for the vertical direction revealed that frequency range of 0-40Hz has the highest energy imparted to the casters and wheelchair frame. The vertical axis has a log scale. The samples per segment This range in addition to frequencies specific for each caster model (between 0-100Hz) were certainly amplified on the caster test. Sensor noise is evident at the frequencies of 24, 48, 96 and 144 Hz.

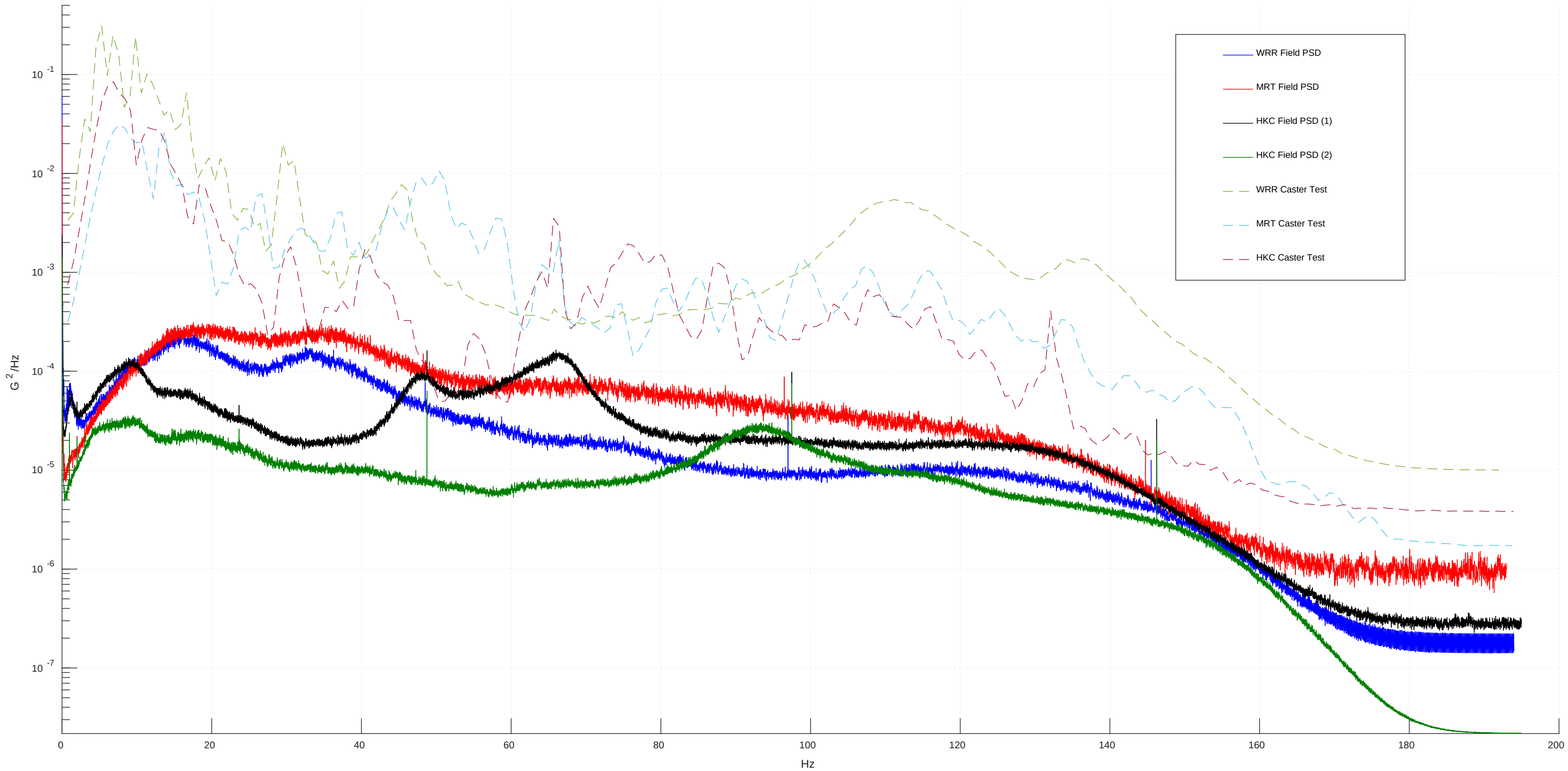

Figure 20. PSDs of accelerations seen by caster models and their wheelchair frames in the field

4.3.1.3 Histogram Correlation

Acceleration data from the field and caster test was binned into bins of 1g interval. Figure 21, Figure 22, and Figure 23 show the distribution of vertical accelerations seen with casters in the field. Note that accelerations from -2g to 4g have not been shown to improve the visibility of the data in the extreme bins. User 1 of the HKC was considered as the extreme user of HKC model and thus, User 2 was omitted from further data analysis. Bending stress analysis to determine accelerations that are responsible for fatigue is shown in Appendix E in sections E.1 and E.2. Based on the analysis, acceleration range between 7g-16g for WRR and 6g-13g for HKC was considered for comparison. Accelerations recorded on the caster test with different slat conditions were combined suitably to make the count in each bin for both models.

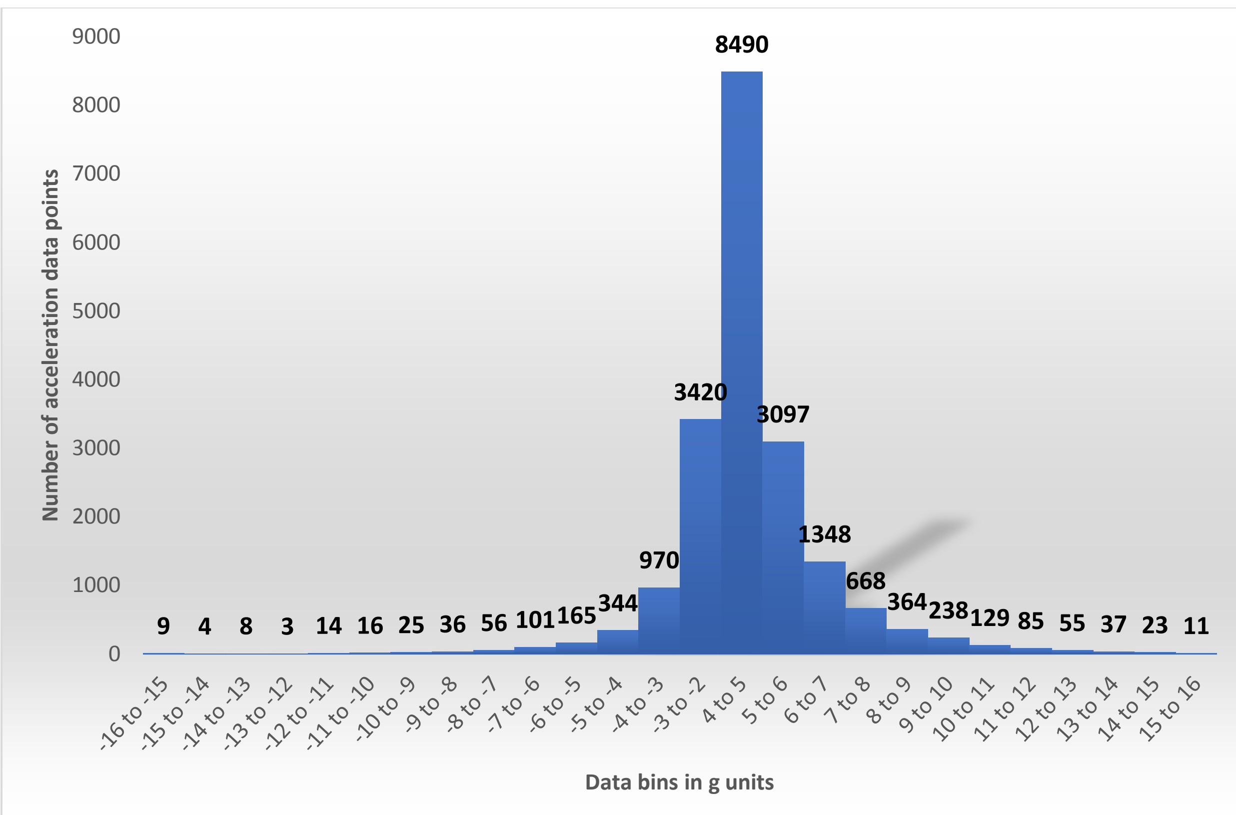

Figure 21. Accelerations seen by the WRR caster in the field (only one user)

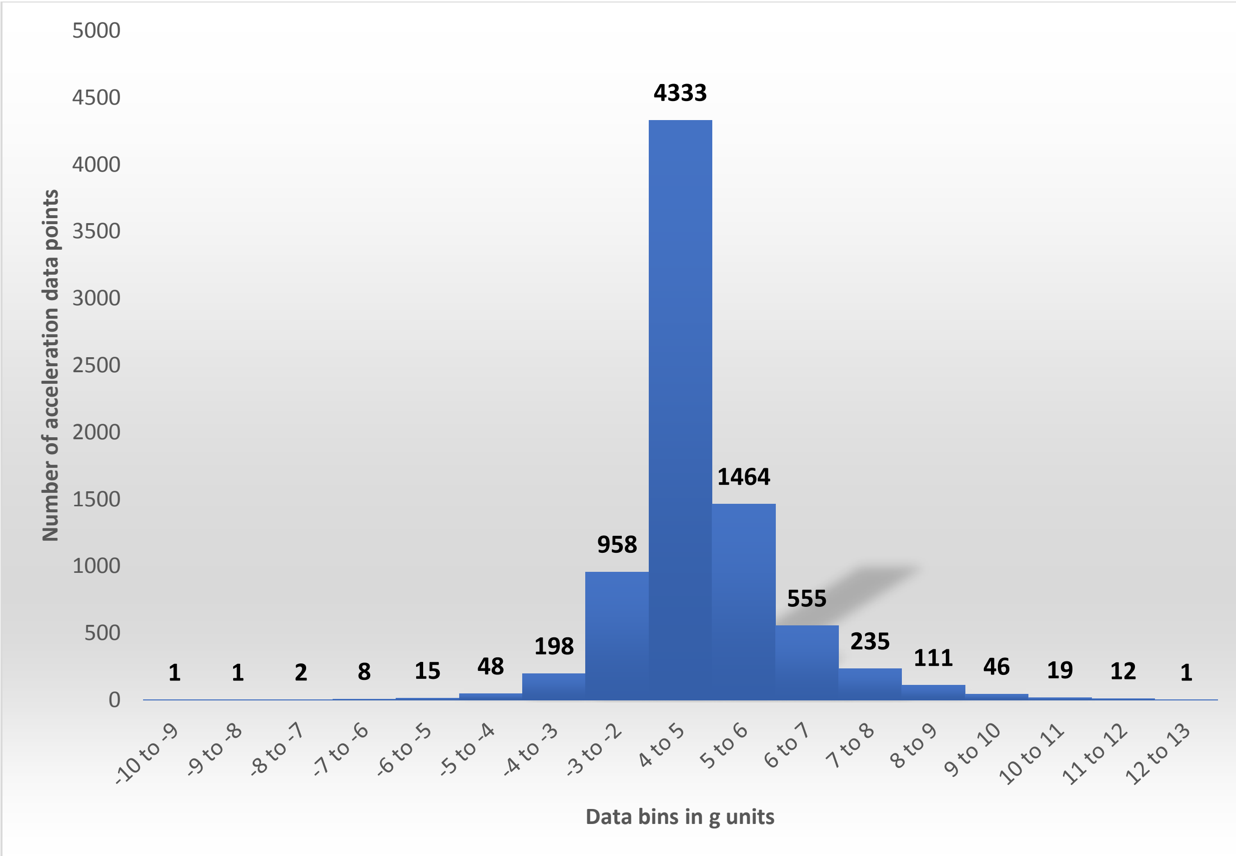

Figure 22. Accelerations seen by the HKC caster in the field (User 1)

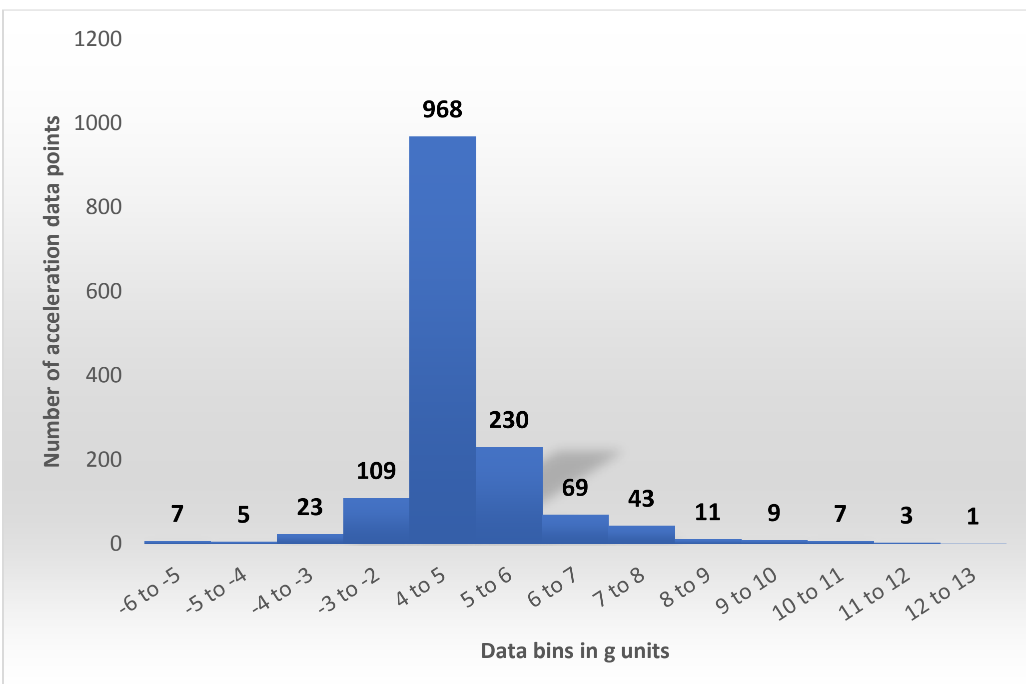

Figure 23. Accelerations seen by the HKC caster in the field (User 2)

Chi-square goodness of fit testing showed that the there is no significant difference between the field and caster test shock exposure distributions for both models [WRR: χ^2 (128.38, 17) << 0.05; HKC: χ^2 (76, 9) << 0.05] which indicated that the new exposures does not correlate with respective field exposures. Figure 24 and Figure 25 show the acceleration distribution matching for WRR and HKC casters respectively. Chi-squared distances were reduced between the field and caster test shock exposures were reduced with validation.

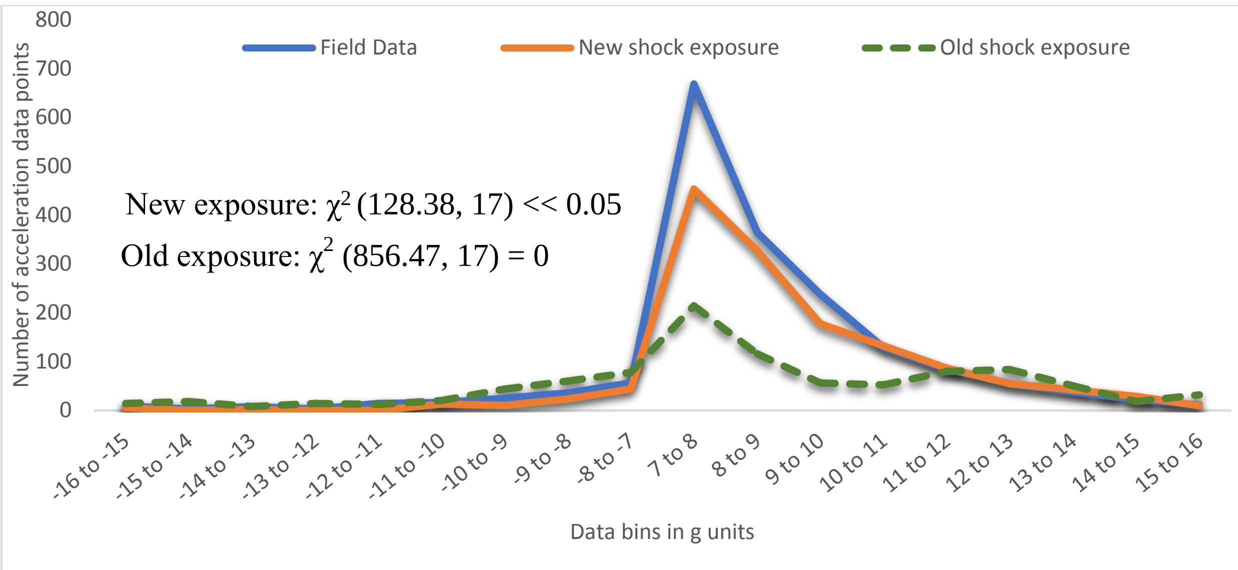

Figure 24. Field and caster test shock exposure histograms for WRR caster

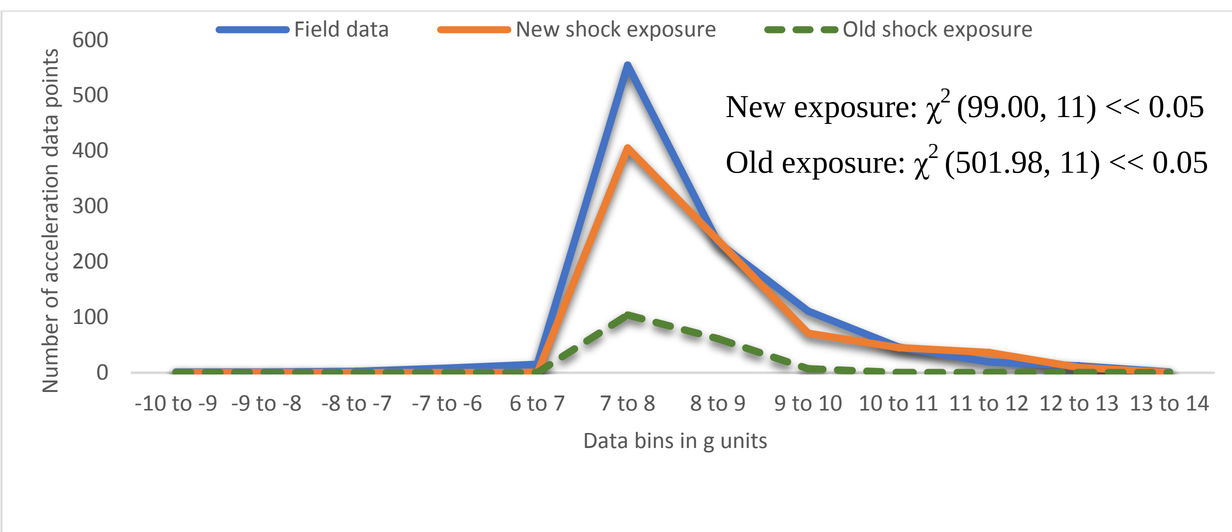

Figure 25. Field and caster test shock exposure histograms for HKC caster

4.3.1.4 Validated Shock Testing Protocol Outcomes

The manually selected combination of shocks from different slat patterns to match field shock distribution suggested a difference in the shock testing method based on caster diameter. Table 19 shows the validated shock exposure or slat pattern for caster testing. Shock exposure is divided into low and high magnitude depending on the slat height. For casters less than 6 inches in diameter, the low and high magnitude shocks can be simulated at the same time on the turntable unlike the other group which requires interchanging the two shock exposures.

Casters are known to reverse their direction of travel for 10% of the total travel [125] and this was simulated by rotating the turntable in reverse every 900 forward cycles. The caster test program was modified (see section E.3) for reversing the motor direction.

Table 19. Slat patterns for caster testing

<table>
<tr><th>Exposure</th><th>Cycles for one-year exposure</th><th>Slat Height</th><th>Number of slats</th><th>Speed</th><th>Direction of turntable rotation (cycles)</th></tr>
<tr><td colspan="6">For WRR caster and casters less than 6 inches in diameter</td></tr>
<tr><td>Low-magnitude</td><td>4500</td><td>0.25in</td><td>n=2</td><td>1m/s</td><td>Forward (4100)
Reverse (400)</td></tr>
<tr><td>High-magnitude</td><td>1500</td><td>0.5in</td><td>n=1</td><td>1m/s</td><td>Forward (1300)
Reverse (200)</td></tr>
<tr><td colspan="6">For HKC caster and casters greater than or equal to 6 inches in diameter</td></tr>
<tr><td>High-magnitude</td><td rowspan="2">3000</td><td>0.75in</td><td>n=1</td><td>1m/s</td><td rowspan="2">Forward (2700)
Reverse (300)</td></tr>
<tr><td>Low-magnitude</td><td>0.5in</td><td>n=2</td><td>1m/s</td></tr>
</table>

4.3.2 Corrosion validation results

4.3.2.1 Collecting outdoor corrosion rates

The online search for corrosion data (for carbon steel) yielded corrosion rates in 12 different parts of the world (See Table 20).

Table 20. Steel corrosion rates seen in different countries for carbon steel

Country	Corrosion rate in mm/year
China[126]	0.1-0.9
India[127, 128]	0.043-1.6
Saudi Arabia[129]	0.0023-0.536
Mexico[130]	0.01-0.298
Colombia[131]	0.0064-0.168
Canary Islands, Spain[132]	0.0038-0.263
Australia[130]	0.348-0.42
South Africa[133]	0.047-0.26
Japan[133]	0.08-0.89
United States[133]	0.005-1.070
Durban, Bluff, South Africa[133]	2.19
Panama[133]	0.991

4.3.2.2 Corrosion evaluation standards

Three ASTM standards were found to evaluate corrosion on painted or coated specimens as shown in Table 21 [134-136]. ASTM G1 was chosen to evaluate the corrosion rate with mass loss test panels in validation experiment as corrosion rate was calculated in terms of millimeters/year similar to outdoor rates reported in Table 20.

Table 21. Corrosion Evaluation Standards

Corrosion Evaluation Standard	Method of evaluation	Outcome of evaluation
ASTM D610 - Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces [134]	The standard presents different rust distribution types seen typically on metals and provides a rating based on the amount of rust seen on the specimen.	Percentage of area covered in rust is converted into a rust grade from 0-10. Fail/Pass is subjective to the user.
ASTM D1654 - Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments [135]	The standard talks about a scribe test that requires making a scribe on the tested specimen and evaluating the increase in thickness of the scribe over the period of exposure.	The increase in scribe thickness is converted into a rust creep rating from 0-10. Fail/Pass is subjective to the user.
ASTM G1 - Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens [136]	The standard specifies a method to evaluate corrosion rates depending on mass loss and time of corrosion exposure.	The outcome is corrosion rate calculated using the formula: Corrosion Rate = (K x W)/(A x T x D) where: K = a constant T = time of exposure in hours, A = area in cm2, W = mass loss in grams, and D = density in g/cm3

4.3.2.3 Corrosion Validation Experiment

SAE 1008 steel panels were used for corrosion in the salt fog chamber. Three panels were cleaned and placed in the salt fog chamber for constant fog exposure at 48°C with high relative humidity (about 97%). Weight loss on test panels was evaluated every 100 hours till 300 hours on a weight scale. Prior to weighing, panels were cleaned, and all rust was scraped from the panels (see Figure 26) surface using a scrubber as specified in ASTM G1 and ASTM B117. Chemical cleaning was not conducted as prescribed in these standards.

Figure 26. Mass loss test panel before corrosion (left), corroded panel after 100hrs of salt fog exposure (center) and cleaned panel before weighing (right)

Mass loss seen with the three panels over 100 hours of exposure ranged from 1.33-1.5 grams. The corrosion rate (averaged for three panels) experienced was 1.5mm/year every 100 hours of salt fog exposure. Comparing this result with the corrosion rates in Table 20, 100 hours of salt fog exposure can simulate corrosion equivalent to 1 year of outdoor corrosion.

4.3.3 Abrasion validation results

4.3.3.1 Tire wear data collection

Table 22 shows the tire wear experienced by different casters.

Table 22. Abrasion rate seen by wheelchair casters in Kenya

Model	Months of use	Number of casters	Reduction in tire thickness/month (inches)
FWM Rubber Tire	14.67 ± 4.62	n=3	0.033 ± 0.003
HKC	12.0 0.00	n=2	0.045 ± 0.03
MRT	8.00 ± 0.00	n=1	0.0375

4.3.3.2 Abrasion simulation on caster test

Sandpaper of 20 and 36 grit sizes was attached to the turntable to simulate rough surface. To evaluate the rate of tire wear, two new HKC samples were tested. Slats were bolted through the sandpaper and the pattern was based on validated shock testing. Reduction in tire thickness was calculated following shock exposure corresponding to one year of outdoor exposure. Figure 27 shows the setup for abrasion validation experiment with the 36-grit, 30 inches wide sanding disc. The tested models experienced wear of 0.0725 ± 0.0275in with 36-grit sand paper[7] compared to 0.02 ± 0.01in with the 20-grit sand paper[8]. Comparing the abrasion rate with that experienced in the field (Table 22), the 36-grit sand paper was chosen for abrasion testing.

Figure 27. Sanding disc attached to the turntable to simulate abrasion

[7] https://www.mcmaster.com/#4700A861

[8] https://www.mcmaster.com/#4700A861

4.3.4 Caster testing results using validated testing protocol

Caster Testing was conducted with 8 caster models as shown in Figure 28. Five of these models (model A, B, D, F and H) are used on wheelchairs distributed in LRS. Model H represents casters used typically on hospital and transportation wheelchairs in LRS. Models D and E are used on standard wheelchairs distributed in resourced settings. Wheels of models A and B are less than 6 inches in diameter unlike others. Caster wheels and stem bearings of models F and G are similar. Samples were tested in the corrosion chamber with stem bearings covered by hollow tubes of proper diameter to simulate stem housing on wheelchairs (see Figure 29). Results of this testing are presented in Table 23. For casters greater than or equal to 6 inches, equivalent number of test cycles have been reported since the slat pattern was interchanged between low and high-magnitude shock exposures. Across the tested models, abrasion + shock and corrosion + abrasion + shock conditions were found to have a significant effect on durability for model D casters ($p<0.05$). Lack of variance in the same group for model A made statistical comparison impossible although the corroded samples failed in nearly half the time as their non-corroded counterparts in the shock testing group.

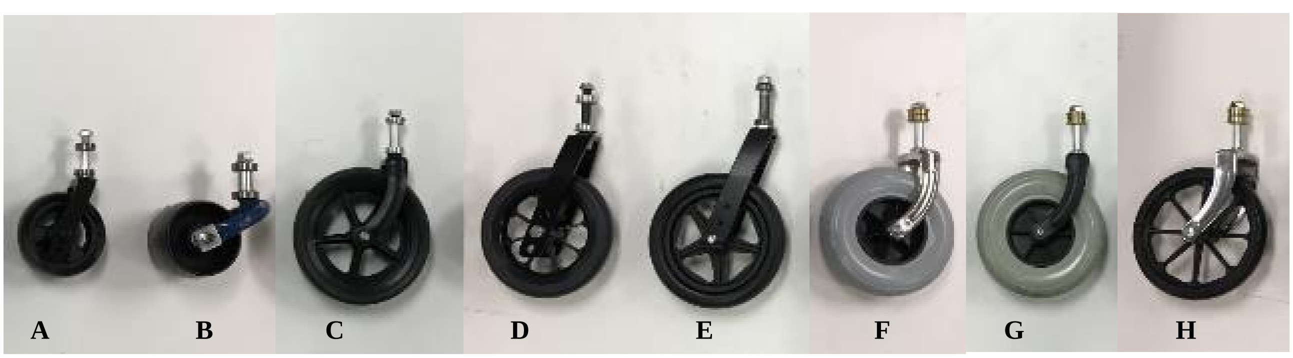

Figure 28. Caster models A-H used for testing

Figure 29. Casters exposed to corrosion in the salt fog chamber

Table 23. Results of caster testing

Caster model and testing condition	Cycles to failure	Failures and test findings	Representative years of use outdoors	Similar to field failure?
A (Shock Testing)	18533.00 ± 0.00	All casters had the same failure mode. Tires delaminated and were scraping against the fork. The corroded samples had mild corrosion	6.17	No
A (Corrosion + Shock Testing)	11000.00 ± 0.00		3.67	No
A (Abrasion + Shock Testing)	Samples unavailable for testing			
A (Corrosion + Abrasion + Shock Testing)				
B (Shock Testing)	43247.5 ± 3478.5	The fork has an aluminum tube welded to it which cracked. Mild corrosion was seen on the fork. Fasteners and axle had heavy corrosion.	14.42	No
B (Corrosion + Shock Testing)	51399 ± 10712		17.13	Yes (mild corrosion on fork)
B (Abrasion + Shock Testing)	38340 ± 9275	One sample had an early fork crack at 29,065 cycles compared to casters in the other two groups. The other sample had a tire crack at 47,615 cycles. One side of both the tires wore down significantly.	12.78	Yes (tire worn-out)
B (Corrosion + Abrasion + Shock Testing)	45411 ± 4025.5	One side of both the tires wore down significantly.	15.14	Yes (tire worn-out, mild corrosion on fork)
C (Shock Testing)	8265 ± 6972	Axle hub assembly came apart. Bent fork as seen as the caster collapsed.	0.92	No
		Stem bolt fractured		No
C (Corrosion + Shock Testing)	8115 ± 1782	Stem bearing fractured. Axle bearing mild corrosion.	0.9	Yes
		Axle bearing came off from the pocket, axle bolt became loose and the assembly began to come apart. Mild Corrosion of axle bearing.		Yes (mild corrosion)

Table 23 (continued).

C (Abrasion + Shock Testing)	9040.5 ± 4120.5	Axle bearing out of wheel pocket, wheel pocket enlarged. Tire worn-out and tread lost.	1	Yes
		Fork fractured. Tire worn-out and tread lost.		
C (Corrosion + Abrasion + Shock Testing)	539.0	Only one sample was tested whose axle hub assembly loose initially.	0.06	No
D (Shock Testing)	91011.0 ± 0.00	Axle bearing assemblies became loose over the course of testing. Axle bearings were seen slightly out of wheel pocket. Corroded samples had loose, corroded stem bearings at 22,665 test cycles that made noise.	10	No
D (Corrosion + Shock Testing)	90128.0 ± 0.00			Yes (axle and stem bearings, mild corrosion)
D (Abrasion + Shock Testing)	33582.5 ± 4992.5	Tire worn-out, tire cracking. The wear was not consistent around the tire.	3.73	Yes
D (Corrosion + Abrasion + Shock Testing)	41711 ± 3080	Tire worn-out, tire cracking. The wear was not consistent around the tire. Corroded samples had loose, corroded stem bearings at 18,500 test cycles that made noise.	4.63	Yes (axle and stem bearings, mild corrosion)
E (Shock Testing)	34252 ± 1100	Stem bolt fractured. One corroded sample had locked stem bearings at 13,500 cycles. Corrosion on bearings.	3.81	No
E (Corrosion + Shock Testing)	57897.5 ± 18935.5		6.43	Yes (mild corrosion on bearings)
E (Abrasion + Shock Testing)	39564.5 ± 15564.5	Significant tire wear and stem bolt fracture.	4.39	Yes (tire cracking)
		Caster suffered tire cracking early compared to other samples and the tire was worn-out unevenly. Fork bent.		
E (Corrosion + Abrasion + Shock Testing)	37363.5± 1968.5	Stem bolts fractured.	4.15	Yes (mild corrosion on bearings)
F (Shock Testing)	22615 ± 115	Bent forks. One sample had the axle bearing come out slightly.	2.51	No

Table 23 (continued).

F (Corrosion + Shock Testing)	25938 ± 3438	Forks fractured.	2.88	Yes (fork heavy corrosion, stem bearing mild corrosion)
F (Abrasion + Shock Testing)	Samples unavailable for testing.			
F (Corrosion + Abrasion + Shock Testing)				
G (Shock Testing)	32739.5 ± 5143.5	All the bottom stem bearings fractured. The stem bearings became loose and were locking very early around 13,000 cycles.	3.64	Yes (Axle and stem bearings sticky and locking and with corroded samples, stem and axle bearings had mild corrosion)
G (Corrosion + Shock Testing)	44922.5 ± 13422.5		5	
G (Abrasion + Shock Testing)	27586.5 ± 1003.5		3.07	
G (Corrosion + Abrasion + Shock Testing)	21679 ± 3914	One sample had an upper stem bearing fracture and the other had a fork crack. Bent stem bolts.	2.41	
H (Shock Testing)	2020 ± 2008	Caster wheels fractured.	0.22	No failure reported.
H (Corrosion + Shock Testing)	8314.5 ± 2914.5	Forks fractured. Tire delaminated.	0.92	
H (Abrasion + Shock Testing)	2513 ± 0.00	Bent stem bolts. One caster had tire delamination.	0.28	
H (Corrosion + Abrasion + Shock Testing)	11500 ± 7000	Forks fractured. Tire delaminated.	1.27	

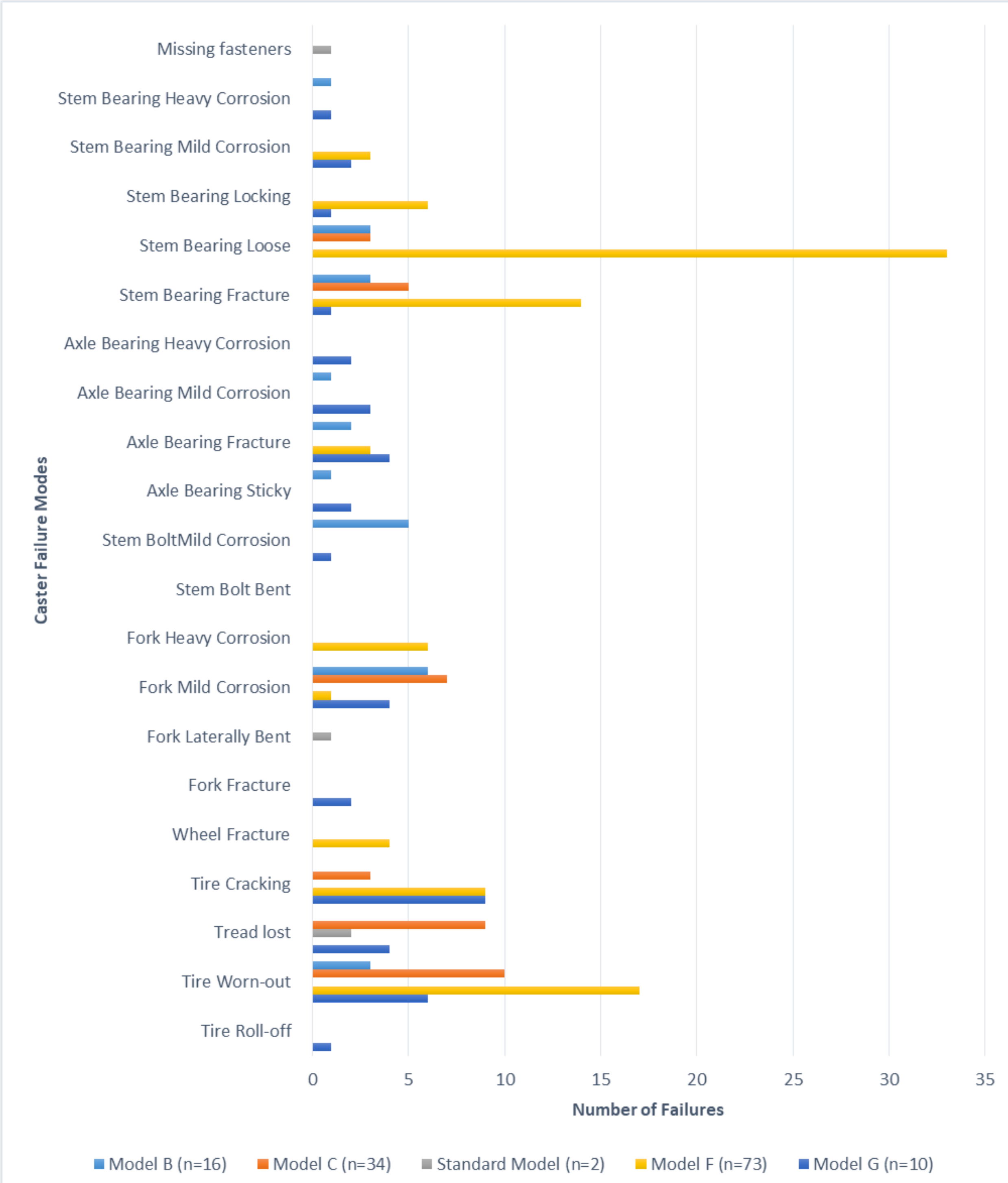

Figure 30. Field failures collected using the caster failure checklist and WCQ-C tool

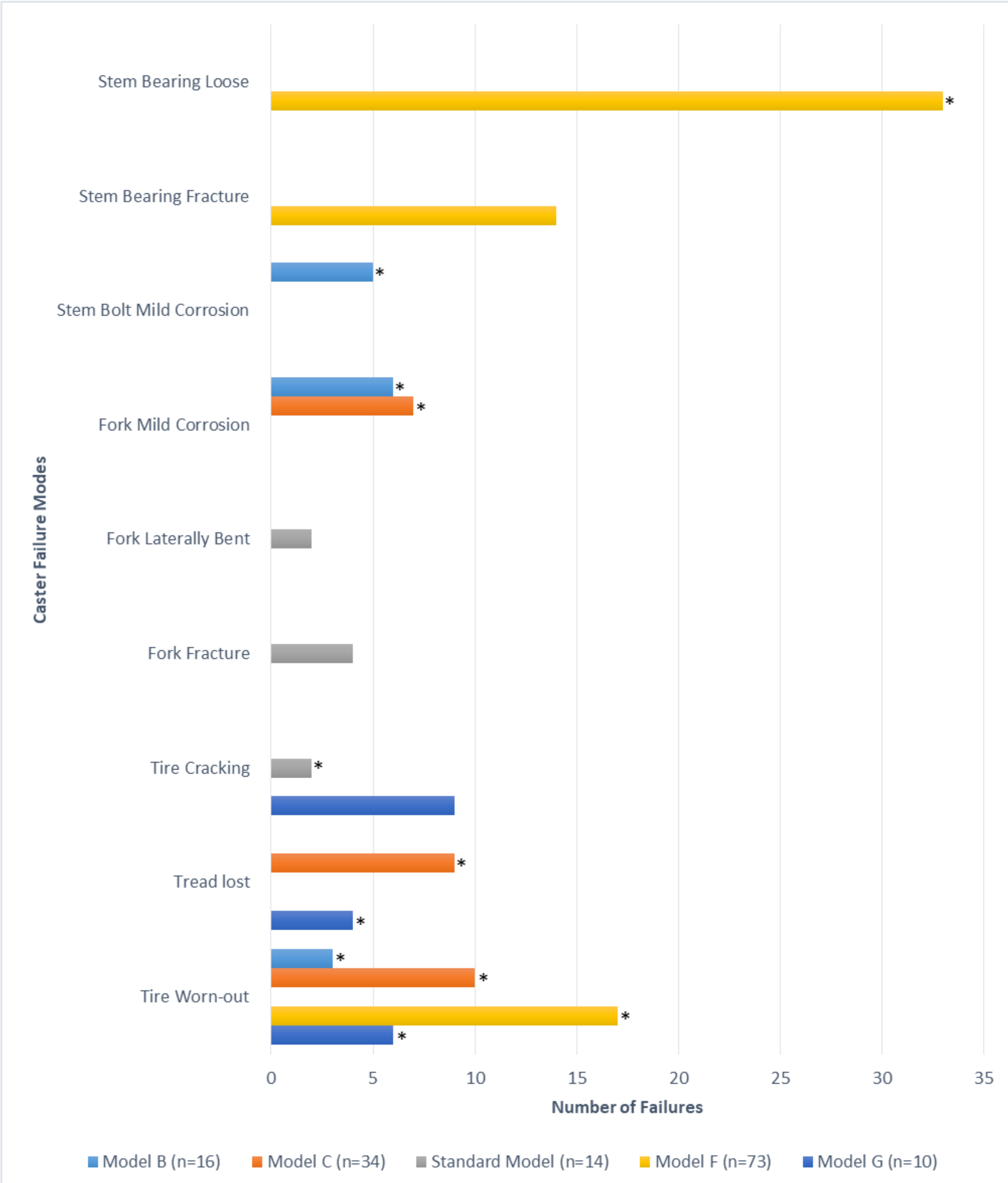

Figure 31. The three most common field failure modes for five caster models, * indicates that the same mode was found during in-lab testing

4.3.5 Correlating testing failures with field failures

Field failures collected for six tested caster models are displayed in Figure 30 and Figure 31. Failures from standard caster models were collected from Scotland and they are similar in design to models D and E. These models are produced by manufacturer of Model D. The rest of the field failures are from Kenya and Indonesia. The period of use for casters varied between 3 months to 6 years.

For each caster model failed in the field, three field failure modes with most failure counts were compared with their testing failures as shown in Figure 31. Tire failures were compared with abrasion tested samples, corrosion and bearing failures were compared with corrosion tested samples and fracture failures were compared with all samples. The number of field failures recorded through non-validated and validated tools were summed up for this purpose. As per comparison, 73% of the three most common field failure modes occurred during in-lab testing. The conditions which included corrosion and abrasion exposures accounted for 10 out of the 11 matched failures.

Fracture failures found in the field data that have high risk for user injuries are fork fractures and axle bearing fractures (see Table 10 in Chapter 3.0). Out of them, the fork fracture failure mode correlated only for model G. Plastic deformation failure related to bending of stem bolts and forks did not match too.

4.4 DISCUSSION

The caster testing protocol was revised based on the feedback provided by wheelchair manufacturers on preliminary testing results. According to them, fracture failures with caster parts happened earlier on the caster test than typically they would in the field. They regarded the test as more rigorous compared to field exposure and the wheelchair testing methods of MDT and CDT. This motivated matching the shocks on the test to field shocks.

4.4.1 Shock validation

Accelerations measured on WRR, HKC and MRT casters in the field and on the test were collected with accelerometers clamped to wheelchairs. A week's worth of data was suitable to characterize shocks seen during normal outdoor use. Initial review of the data showed vibrations clouded around shocks.

To verify the whether the frequencies amplified in the field follow similar trend on the test, FFTs and PSDs were generated and compared. The FFT data was noisy and inconsistent to make any conclusions. The PSDs showed that the 0-40Hz region contains more energy in both the environments which is consistent with findings in earlier studies [122, 137] between 80-120 Hz are amplified on the test which could be attributed to vibrations seen on the equipment (visible in FFTs). These frequencies are certainly less than the fundamental frequencies of the caster parts which negates the possibility of failure due to resonance.

Bending stress analysis assisted in manually filtering shocks that affect fatigue from the vibration data. Accelerations specifically in the vertical direction were considered for analysis as the reaction force (due to user weight) in that direction is responsible for 80-95% of bending stress in the stem bolt. For correlation of field and test shocks to be significant, a suitable combination of slats that reproduce same acceleration levels on test as the field was selected. This resulted in formation of two distinct shock exposures based on wheel diameter. Casters greater than 6 inches in diameter are subjected to a higher size slat of three-quarter inch thickness. This was required as the larger diameter wheels would easily roll over the half-inch without suffering high magnitude shocks. Only one size of this slat could be mounted at a time because it makes the casters bounce over the oncoming slat at times. This situation supported separating the low and high magnitude exposures or slat sizes. Interchanging slats increases the test setup time.

In Figure 24 and Figure 25, the gap between the histograms for accelerations levels in the middle region is quite evident. This is because reproducing these accelerations requires employing slats which are less in thickness than the ones in the low-magnitude shock exposure. Less than 0.25in for small casters and less than 0.5in for the larger ones would have needed to be added. Adding these slats would have significantly increased the testing time and hence, they were left out.

4.4.2 Corrosion validation

Salt fog testing is used in different industries solely for comparing the corrosion effects between different test materials. The test is widely used because it is reliable and conducts accelerated corrosion testing through a standard exposure. Unfortunately, there is no correlation evidence between corrosion effects seen with salt fog exposure and field exposure. This lack of evidence may be because the corrosion inducing mechanisms seen outdoors are quite different compared to the salt fog chamber.

Unavailability of actual field failure samples to compare corrosion necessitated comparing corrosion rates reported in literature.

4.4.3 Abrasion validation

Sandpaper was considered a suitable medium to simulate a rough surface because of its consistency to cause abrasion. Maximum abrasion occurs when tires scrub on rough surfaces compared to rolling. Casters on the turntable are continuously scrubbing and the scrub is enhanced when the caster flutters after a slat hit. It should be noted that the abrasion validation did not include comparison with abrasive elements like sand, gravel and sharp stones. Comparing abrasion across surfaces is the next step for abrasion validation.

4.4.4 Validated caster testing

Caster testing with validated conditions exposed the shortcomings in caster quality. Caster samples exposed to the same condition incurred similar failures except for those with poor quality parts. This demonstrates the strong internal validity of the test which was also found with preliminary testing. Tested caster designs in the study were representative of the casters used on wheelchairs in RS and LRS. Introduction of the environmental testing factors – corrosion and abrasion impacted the durability of 25% caster models and altered failure modes for 75% of the tested caster models. Two out of the three altered failure modes due to inclusion of environmental factors have significant risk of causing injuries to users and wheelchair failures. Only one model had poor quality parts and tolerances and its samples failed inconsistently disregarding the condition they were tested against. Discussing the performance of each model in detail can help elucidate the impact of environmental conditions and differences, if any, between the field and test failure modes. Our results demonstrate the importance of including environmental exposures in wheelchair durability testing, which historically has not been performed.

4.4.5 Model A testing performance

Corrosion impacted model A; the corroded samples suffered tire delamination failure in nearly half the time compared to their non-corroded counterparts. There are two important reasons for this failure mode. Delamination is a result of poor bonding between tire and the wheel. And exposure to humid conditions makes polyurethane loose, which is known to wheelchair designers and technicians. Corrosion exposed these deficiencies with the model as shown in Figure 32.

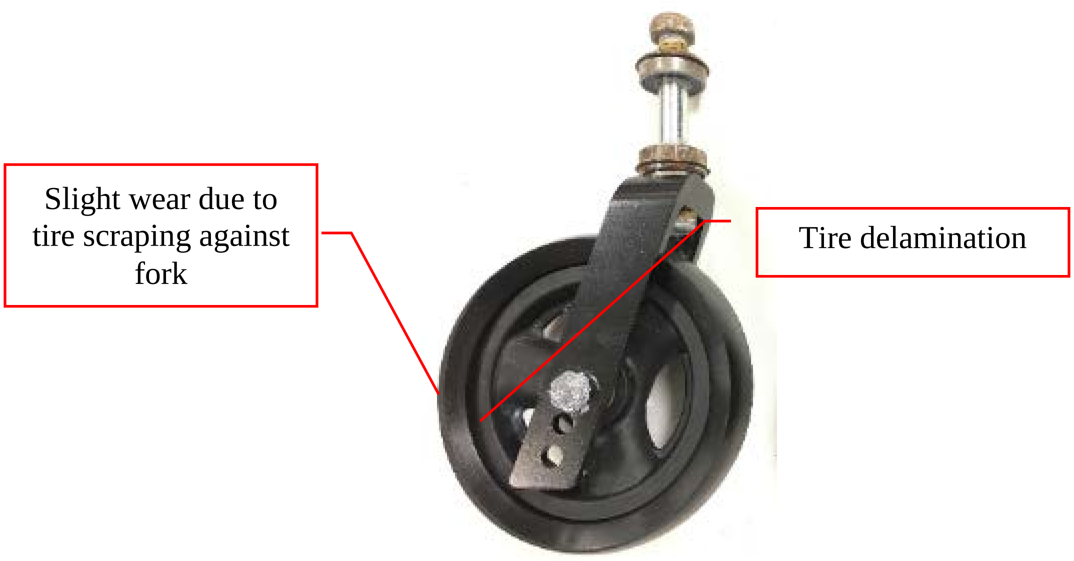

Figure 32. Corroded sample of model A

Tire roll-off and wear on the sides of the tire could have been the potential failure modes if testing was continued. On one hand, this failure may not occur in the field because the caster is mounted on a three-wheeled wheelchair and bears less than half the standard load used for testing. Using loads based on position of the caster on the wheelchair can be considered in the future.

4.4.6 Model B testing performance

Wheelchairs with model B casters are produced locally in LRS. Its rubber wheel is made from auto tire retread rubber with some additives which is molded over standard bicycle hubs. The design and quality of the caster parts and tires does vary based on the place of production which is a quality assurance issue. This issue has known to cause tire worn-out and cracking failures. They are quite common in the field but were found late during testing with abraded samples. This outcome was anticipated because the caster did not flutter much after slat hits that was necessary for abrasion. This indicates the need for an alternate abrasion approach. The caster did flutter eventually after around 25,000 as one side of the tires was worn out more (see Figure 33).

Figure 33. Worn out tires of abraded model B samples. Tire cracking failure (right).

Figure 34. Fork cracks in model B samples.

Cracking in the fork as shown in Figure 34 was a consistent failure among samples and this fatigue failure is not seen in the field. When this failure was discussed with the manufacturer, the design provided for testing was inconsistent with the manufacturer specification. This calls for quality assurance with wheelchair production. The fork is coated with blue paint which did experience mild corrosion after 100-200 hours of salt fog exposure similar to the field.

Bearings of this model are robust. Axle bearings were sticky after corrosion but did not have any issues due to fatigue. Stem bearing failures found in the field were not seen with testing. Based on previous experience with this model, it can be said that high quality samples were provided by the wheelchair parts supplier for testing. That could be the reason for no bearing failures and late abrasion related failures.

4.4.7 Model C testing performance

Several inconsistencies were found with parts of model C. The caster wheel pocket accommodating axle bearings lacked in tolerance. Hard, polyurethane tires could not absorb shocks that transferred to the rest of the assembly. During testing, the fork pressed constantly on the threads of the axle bolt which caused the hub assembly to loosen gradually. Stem bearings lack tolerance. Shortcomings like these may have led to a mixed set of failure modes (see Figure 35) during testing and likewise, in the field. The manufacturer uses two styles of tires – rubber and polyurethane, and the type of tire is not reported in the field data. The polyurethane tires lost tread very early on during testing which is in consensus with the field data.

Figure 35. Failures with model C

4.4.8 Models D and E testing performance

Models D and E are used on standard wheelchairs in RS. High quality parts are used on both casters except that the axle bearings on D have loose tolerance (see Figure 36) which resulted in loose hub assemblies and bearings coming out of pockets during testing. Corrosion did not have an effect on them except rusting the bearings. With samples in the corrosion + abrasion + shock conditions, the axle bearings became loose early. Loss of tread, tire wear and cracking were found as both models fluttered a lot causing rapid tire wear down.

Figure 36. Model D failures. Shock tested samples (left and center) and abrasion + shock tested sample (right)

Figure 37. Model E failures. Shock tested sample (left) and abrasion + shock tested sample (right)

Field failures were collected at a repair facility and the cause of these failures were noted by the repairer. Most of them were due to impacts. Comments provided by the repairer indicate that most failures known to occur with standard casters are fracture failures from impacts. For example, fork fractures caused by curb impacts. This evidence suggests the need for including impacts at suitable intervals of caster testing.

Stem bolt fractures seen with testing because of fatigue (Figure 37) were not seen among field failures. These failures although were evident with power wheelchair casters whose field data was available for use but was not included for review in this study. They were a result of impacts too which makes a strong case for including impact testing.

4.4.9 Model F testing performance

Model F forks were affected by the looseness in hub assembly. The wheel pockets for accommodating bearings were out of tolerance that made the forks bend laterally during testing. This failure was enhanced when corroded samples were tested. Corners of the corroded forks were rusted and the double impact of corrosion and shocks led to fork cracking as shown in Figure 39. Chrome plated forks was found to be easily rusted. The pitting caused on the surface by rust are hot spots for cracks to emerge. Figure 38 shows the small pockets formed on the surfaces of fork.

Figure 38. Corrosion effects on a chrome plated caster fork

Figure 39. Model F failures. Shock tested sample (left and center) and corrosion + shock tested sample (right)

Majority of the field failures were tire failures and stem bearing failures found within two years of use. The caster wheels are same as model G which did experience tire tread wear. This caster tire is an interesting case; the soft polyurethane absorbs shocks but once the tire dressing and tread wears out, patches and holes in the tire material begin to appear shown in Figure 40. In this condition, if the tire is exposed to humidity and rocky surfaces, the holes and tire can tear up as shown in Figure 41. This evidence encourages a cyclic testing approach instead of a cascading testing approach. Casters can be cycled through corrosion and shock + wear testing following a representative year of exposure to each condition.

Figure 40. Irregularities found in the tire once the tire dressing comes off.

Figure 41. Wear issues reported with tires of models F and G in the field

Stem bearing designs varied for model F as shown in Figure 42. All bearings had the same size but the seal type was different. Some bearings had a rubber seal (with grease leakage) while some had a metallic shield (same as model G). The set with rubber seals was chosen as the other style were not sufficient in number for testing. The bearings were loose initially due to tolerance issues but there were no failures observed with testing. Stem bearing fractures are evident in the field with this model. If model G style stem bearings (provided with model F) were used for testing, fracture failures could have matched because nearly all bearings on model G fractured.

Figure 42. Bearings used with model F (left and right) and model G (right) casters

The discrepancy with variety in bearing design can be generalized to most wheelchairs distributed in the field by charitable organizations. Absence of quality checks on the supplier side leads to parts being supplied as long as they meet the manufacturer specification. Moreover, quality of parts varies between production batches. This is a constant concern reported by wheelchair providers and this drawback affects comparison of failures across different settings.

4.4.10 Model G testing performance

Stem bearings on model G (see Figure 43Figure 41) were low quality because they locked randomly and acted as bushings prior to any testing. Some bearing samples were corroded on the inside; the rust could be observed beneath the metal shield. Corrosion exposure made the bearings worse. During testing, the balls inside the bearings would get crushed but the bearings would still hold up. The fracture used to happen when inner race separated out from the bearing assembly during testing as shown in Figure 44. Stem bearing locking and fracture failures were noted between 2-3 years of use with testing. The fracture failures are consistent with the field data for stem bearings of model F that uses bearings of model G style. Time to failure matches as well.

Figure 43. Stem bearings supplied with model G for testing

Figure 44. Failure mode seen with model G, bearing fractures (left) and fork crack (right)

Axle bearing issues were found with four samples between one to three years of use. The model has a loose hub assembly which strains the fork laterally. Impacts can affect them more which could be happening in the field and hence, the axle bearing and fork failures were seen outdoors.

Bent stem bolts and a fork fracture was found with corrosion + abrasion + shock testing. Corrosion of fork and loss of tire material are potential causes which again demonstrates effect of environmental factors altering the failure mode. Two fork fractures were found in the field with this model, but fork fracture is not a leading failure.

The black painted forks of model G did not corrode as much as the chrome plated forks of model F indicating that painting is better for corrosion resistance compared to chrome plating.

4.4.11 Model H testing performance

Model H was considered representative of the caster style used on hospital and transportation wheelchairs in LRS. The model was easily affected by corrosion and abrasion. The chrome plated forks were constantly under stress in the lateral direction due to poor tolerances of the hub assembly which led to fracture failures. Fork cracking occurred specifically with corroded samples. The abraded samples incurred bent stem bolt failures. Model H testing failures are shown in Figure 45. Tire delamination was a common failure across all samples which happened quite early in testing. No field failures were found for this caster model.

Figure 45. Model H testing failures. Wheel fracture (left), fork crack (center) and bent stem bolt (right)

4.4.12 Correlating field and testing failures

Field data and the results of validated testing show that corrosion and abrasion significantly affect caster parts and add to fatigue which strongly suggests the addition of these environmental factors in the caster testing protocol. Further, a 73% match of leading field failures with caster testing failures indicates that caster test has substantial capability to simulate outdoor failures correctly with respective models and this represents the test's strong external validity. Ninety percent of the matching failure modes are because of the environmental factors. Corrosion makes fatigue failures worse which multiplies the risk for user injury.

Field data was collected from different sources and the period of use had significant variability and greater range. Certain failure modes were found to be common and matched with the failures seen with the same model however, the duration of use did not equate well with the representative years of use seen with testing. While establishing such an equivalence was not the objective of the study, it is an important correlation to consider in the future studies.

Tire failures as seen with standard casters (models D and E) were not evident in the field. This is because the field data came from resourced settings where there are paved streets with smooth surfaces. If such standard casters are used in LRS, they will crack and wear out as seen with testing. This study finding is in consensus with the tires issues reported with standard casters and casters (model H) used on hospital style wheelchairs in LRS [89].

When fracture failures that have high risk to user injuries were compared, none of them were simulated on the caster test. Stem bearing fractures correlated for models C; this failure was not among the top two leading failures. There were two fork fractures noted with model G and one samples incurred this failure mode. It was surprising to note that none of the models had stem bolt fractures in the field which is a common fatigue failure on the test. Comments received with caster evaluations can provide the reason for this. The technicians reported that fracture failures (as reported for standard models) occur due to impacts. Impacts cause parts that are fatigued or loose to fracture easily. More field data is necessary to inform inclusion of impacts in the caster testing protocol.

In the testing study, the number of years of representative outdoor use for caster ranged from a few days to 15 years. For some models, the number of years they lasted as per the test was very optimistic. Anecdotal report from the designer of model B casters says they are known to last up to 8 years [18]. On the test, they sustained sufficiently longer than that. This highlights discrepancy in shock correlation. Correlation was based on acceleration data collected with two users. Similar data from more users from different settings is required to modify the correlation equation for number of years. Analysis of more data may also suggest adjustments to the shock pattern i.e. size of slats and amount of exposure.

4.5 LIMITATIONS

There were several assumptions and limitations with the shock validation approach. The load on the caster for validation purpose was lower than typical standard load on casters (30lbs) because of two reasons. Firstly, testing with standard load did not produce accelerations as high as those seen in the field. Employing thicker slats (to increase accelerations) amplified the fatigue process and caused early fracture failures. Secondly, the users were from a pediatric population.

Sample size of users from whom the acceleration data on casters was collected was small. The WRR exposure on the caster test is based on only one user who was deemed as the extreme user. The condition of wheelchair casters and the information about health, weight and activity levels of the users were unavailable.

Limitations with the sensor are related to range specification, location of mounting and orientation. Shocks and impacts above ±16g for the WRR and MRT casters could not be recorded in this study due to limitations with the sensor specifications. The half inch slats produced higher accelerations for smaller caster, but peaks were observed that went over the sensor range.

Location of mounting the sensor was different in the field and on the caster test. On the caster test, the sensor was mounted on the caster fork because the caster arm absorbed most shocks. When mounted on the fork, the sensor would change its orientation sometimes because of shocks. For the HKC wheelchair, the sensor was mounted on the frame member between the two casters and on this model, the casters are closer to the rear wheels. This can cause rear wheel accelerations to be recorded.

Standardized evaluation of test panels following corrosion required chemical cleaning which was not performed. Chemical cleaning may cause greater mass loss of the test panels which can mean that the 100 hours of exposure to simulate a year of outdoor exposure is overestimated.

Abrasion validation is conducted with only two samples of a single model. More failed models need to be collected to validate the dosage of abrasion. Abraded rubber and polyurethane gets accumulated in the sandpaper which impacts the rate of abrasion during testing.

While the study compared field and laboratory tested samples, variability in the quality and design between field and tested samples is unknown. This may have skewed the failure modes and affected the comparison conducted in this study. Also, there is no data available on the maintenance, repair and replacement status of the field casters.

One data point of interest is the tightening torque for caster stems which is unavailable from manufacturers, suppliers and providers. Apparently, technicians tighten the stems based on experience and user ability. The tightening torque affects the behavior of the caster on the test. More the flutter, greater the tire wear. The standard casters were a special case, excessive tightening of the stem bearings would not help with minimizing the flutter. In two samples of model D, rubber bands were attached to avoid casters rotating about the stem. This amplified tire abrasion.

The caster test produces reliable results however, using only two samples in each testing condition caused confusion when failure modes did not match between the two samples. The selection of sample size was conditional on the number of samples of each model that were supplied for testing by manufacturers.

The field failure data came from various sources. The face-validated version of the checklist may or may not produce reliable evaluations and data. The WCQ-C tool is a validated questionnaire however, the data available to gather field failures was negative comments provided by raters on conditions of field casters. Decoding the comments and fitting the failures in comments to failure modes in the checklist may have some inconsistencies with the actual failures.

4.6 FUTURE WORK

Corrosion and abrasion were found to influence failure modes and both testing factors should be included in the testing protocol. Future work for caster testing deals with the need for further validation of the testing factors, suggesting modifications to design of caster models based on testing results and publication of resources that are useful for the wheelchair sector.

Data available for validating the three testing factors was limited in several respects. This impacted the respective exposures that were translated to testing. While results indicate that the testing protocol is efficient in reproducing leading failures from the field, the time to failure did not correlate well. Future work needs to focus on collecting data at different points of caster use with the caster failure checklist from several users in multiple sites in LRS. This data may inform inclusion of other factors such as impacts.

Certain models were found to be sub-par with testing. Manufacturers of these models should be provided with design recommendations and encouraged to perform iterative design and testing. User trials and failure data collection using checklist with improved models can inform regarding outdoor performance, changes to the caster design and upgrades, if any, to the testing protocol.

The caster testing protocol needs to be published as a standard for use by designers, manufacturers, and wheelchair providers. The caster testing team should develop resources which are targeted at different audiences (clinicians, manufacturers, providers and non-governmental institutions) who are stakeholders involved in wheelchair provision. Observations and findings from this study should be translated into caster design guidelines which can assist manufacturers and providers in caster selection.

5.0 CONCLUSIONS, FUTURE WORK AND RECOMMENDATIONS

5.1 CONCLUSION

Wheelchair technology has continued to evolve in the past two decades. Along with the need for wheelchairs, the number of manufacturers has grown rapidly. There are more product options than ever before. Manual wheelchairs have become more lightweight with performance tires and casters. While technology has advanced at a rapid pace, research evidence suggests that wheelchair quality has not improved over time [33, 34, 50, 78]. Field evaluations have reported that wheelchair parts fail within a year or two of use, especially wheelchair casters [95, 112]. With product quality, testing standards that evaluate wheelchair quality and durability have remain mostly unchanged for the last 20 years since publication. One reason for this situation is that field evidence on wheelchair failures has not been utilized to inform standards development. There is substantial research on wheelchair testing with manual and power wheelchairs but the gap between testing conditions in the laboratory (standards) and field conditions has never been evaluated.

This dissertation work evaluates this gap to conduct field validation of laboratory-based testing protocol for wheelchair casters and provides recommendations for caster design and wheelchair testing based on validated testing outcomes. For the development of the protocol, information received from expert feedback, and data from caster testing and field evidence was continually triangulated.

This work was motivated by the need for high-quality wheelchairs highlighted in the international policies, guidelines and wheelchair service provision packages published by the UN, WHO, ISPO and USAID and primarily by product testing recommendations proposed in the WHO Guidelines [1]. The guidelines recommended developing testing standards (in addition to ISO 7176) based on the environmental and use conditions seen in LRS. This directed the research team into reviewing existing literature on standards testing development, wheelchair testing and outdoor wheelchair evaluations as described in Chapter 1.0 . Two important findings from the review were:

- Standard fatigue tests of MDT and CDT were found to best represent conditions in RS which are suitable to test performance and lightweight models used in RS. LRS conditions, as noted by WHO, were not considered possibly due lack of representation on the ISO Technical Committee from LRS.
- Products delivered in LRS are poor quality and ISO tested products fail within a year of use with diverse failure modes.

Wheelchair experts participating in the ISWP-SWG were aware of these issues. During group meetings, several design and performance issues in LRS were discussed for which testing did not exist. Assessment of field failure evidence indicated gaps in standards testing conditions and field conditions in LRS and provided directions for additional testing. The product testing matrix (Table 4) developed by ISWP-SWG experts is a valuable outcome from the group discussions conducted over six months. All testing factors responsible for common failures of wheelchair parts are included. The validated testing approach employed in this dissertation work can be used to develop similar testing protocols for quality testing of different wheelchair parts.

Casters were prioritized for testing as they were voted to fail frequently compared to other wheelchair parts. Also, casters had the largest failure modes as per the product testing matrix. Chapter 2.0 talks about the iterative design approach development of a new testing equipment. For developing the caster testing protocol, an evidence-based approach was followed. Initially, caster failure evidence collected through photographs led to identification of testing factors not included with ISO. Difficulty in integrating additional testing factors into ISO testing methods necessitated development of the caster testing system. The system's design process was directed by the iterative feedback from wheelchair experts with significant field work experience. Shock exposure on the caster test was initially benchmarked to ISO MDT. Results of preliminary caster testing showed consistency in failures for each model indicating a high degree of internal validity for the test. Anecdotal feedback by manufacturers on the results suggested inclusion of additional testing factors and their validation to field conditions. This suggestion prompted collection of field data for validation purpose and field failures to compare testing outcomes. Both suggestions were addressed through two studies presented in Chapters 3.0 and 4.0.

The caster failure checklist was born out of the necessity for a standardized tool to collect caster failures from different settings in a reliable manner. The research team anticipated collecting failures in two ways – 1) physical evaluations during wheelchair repair and maintenance by technicians and rehabilitation professionals and 2) online evaluation through photographs which are sent by wheelchair users in the community. Accordingly, two cohorts were tested. In the physical evaluation group (n=12), 10 out of 14 failure modes received substantial to high reliability scores and 12 items had high accuracy scores. The online evaluation group (n=11) inconsistently rated failures through caster photographs which can be attributed to unclear representation of failures in the data, instructions and rating options. The latter two issues affected physical evaluations too and hence, instructions were revised and explained in greater detail on a webpage which are hyperlinked to checklist failure items. The checklist was disseminated to all ISWP partners with service facilities around the world for collecting caster failures. There has been a mediocre response to completing the checklist mostly because it needs a designated person to evaluate a caster. Familiarizing with checklist items and their evaluation instructions may take time.

Currently, the failure checklist is being employed at two wheelchair service facilities in Indonesia and Scotland. About 14 failures with four caster models have been reported by the two checklist users at these facilities. The users have included the cause for failures in the comments which is a useful detail. If failures are found because of a condition not included in testing (for example, impacts causing forks to break), the failures can be considered for inclusion if the frequency of such failures is high. This approach assists with using field data to inform the testing protocol.

The median time required for filling out the checklist by the two users was 7 minutes. The completion time reduced as the users evaluated more casters. This shows that completing the checklist may consume time initially and with practice, evaluations can be done quicker. Based on feedback from the early adopters, it is feasible to integrate the checklist into regular wheelchair checkups and repair test logs. One wheelchair provider has expressed interest in using the checklist in their training program.

Inclusion of environmental testing factors was required to simulate failures caused by them in the field. Validation was necessary to determine the degree of exposure; for shocks, it was the pattern of exposure. These two steps led to reproduction of substantial number of leading field failures on the test.

Certain fatigue failure modes and the number of representative years did not correlate in this study and there can be three reasons for this. First, the amount of data available for validation was minimal which may have led to discrepancies in dosage needed to simulate the failures. Second, the causes for fatigue failure modes seen in the field showed that heavy impacts and not fatigue were responsible for the failures. Third, variability in the quality and design of models is unknown between the two settings. Standard models compared in the study were not the same. Reliability of the collected data may be questioned as it majority of failures were translated from comments on caster condition and some data came from a non-validated tool. More validation based on field data is required for consolidating the protocol further.

Caster testing results are always of value to the providers and they have always appreciated our feedback. Previously, one provider considered changing the hardness of tires and design of forks based on preliminary testing results. The new style tires were tested and again found not to absorb shocks with the validated testing protocol. This feedback will be shared with the provider and it is anticipated that the provider will continue to test modified designs in the future. Two other providers upgraded the stem bolt diameter and stem bearings on their models after preliminary testing. One model suffered from stem bolt fractures and the other has stem bearing fractures, but it could not be confirmed if testing caused the providers to select a new design. It is great to see that caster testing is affecting provider’s choice of designs and suppliers.

5.2 FUTURE WORK

Future work for caster testing deals with collection of additional field data to inform the dosage and exposure method for all three testing factors, and to explore other factors such as debris.

The pattern of shocks based on caster diameter seems reasonable because fatigue failures like stem bearing fracture and stem bolt bent failures correlated for two models. However, the number of representative years of outdoor use for most models did not. Correlating the time to failure is the next step for protocol validation and additional field data is needed for this purpose. For data collection, the sensor system needs to be preliminarily tested to check if all shocks and impacts seen in the field are measured. Mounting of the sensor should be standardized; the fork or the stem hubs are suitable parts for attaching the sensors.

Another suggestion related to measuring shock exposure is collecting strain data as accelerations may not provide reliable comparison between the wheelchair in the field and the caster arm on which the caster is mounted. Measuring the bending strains suffered by the stem bolt and forks using strain gages is suggested. This will require development of a new instrumentation to capture data. This approach can make it easy to compare data across the two settings and replicate shocks. Testing research conducted by Free Wheelchair Mission[9] is using strain gage instrumentation to evaluate bending stresses and strain on caster stems. The sensors connect with a large size controller which is difficult to attach to a wheelchair. In the field, it is suggested that a microcontroller can be used to record and store such data.

Fork and axle bearings fractures which are the two leading fracture failures from the field did not correlate and so did the stem bolt fractures found with standard model E on the test.

[9] https://www.freewheelchairmission.org/

Comments provided by the repairing technician on some fractured models indicate the fractures are caused by impacts too. This factor is not included in the caster testing protocol. This finding encourages investigating the inclusion of impacts on the caster test. Caster may be impacted by the pendulum after a designated number of test cycles possibly, after every year of simulated shock exposure.

Angled impacts may cause tire-roll off or axle hub fractures in the field. These failures may not happen on the caster test as the current slat configuration simulates angled shocks and not impacts. The size and shape are benchmarked to the ISO multi-drum test slats; the slat's cross-section is a rectangle with half inch height. It is recommended that the slat configuration should be benchmarked to outdoor shock and impact conditions. Modifying the shape and size of the slat or introducing a ramp can be considered to simulate straight and angled impacts to reproduce field failures caused by impacts.

Corrosion validation was conducted with comparing the rate of corrosion of low carbon steels. This rate of corrosion needs to be evaluated with actual samples tested in the field and salt fog. All the three ASTM standards found during validation study can be employed to evaluate corrosion effects. ASTM D610 can be used for evaluating amount of rust on surfaces of forks, ASTM D1654 can used to evaluate the resistance of coatings to corrosion and ASTM G1 can be used to find out the rate of corrosion with bearings, forks and fasteners.

Improvements are necessary to simulate abrasion as all casters were worn-out unevenly. The direction of turntable needs to be reversed for half the number of cycles so that the both sides scrub for the same time. For the reverse direction, the speed needs to be about 5-10% greater to induce the same accelerations as those seen with forward travel. To remove tire material that gets accumulated in the sandpaper during testing, a blower needs to be installed on the test. Some experimentation needs to be conducted to determine the consistency of material removal by a single sandpaper. Also, the sandpaper is great for consistent abrasion but fails to simulate effect of sharp edges which can be seen with stones or gravel with higher grain size. As noted with models F and G earlier, once the tire dressing comes off the inside of the tire is susceptible to easy tear from sharp edges. Experimentation should be conducted to determine a suitable sharp surface.

Abrasion dosage needs to be revised by comparing wear for different models between the lab test and field. This may result in changing the grit size of the sandpaper or use of other abrasion causing mechanisms.

In addition to surface abrasion, there are several environmental factors that cause wear of caster parts. Ultraviolet light (UV), ozone and high temperatures are responsible for degrading plastics, rubber and coatings. Tires with poor quality can harden and degrade quickly. Coatings can harden and flake off from forks which can make forks vulnerable to corrosion. Based on the nature of failures collected from Kenya, it is necessary to include UV, ozone and heat into the caster testing protocol. Casters can be subjected to these environmental testing factors prior to durability testing.

Data needed for further validation can be obtained through a prospective study conducted with users of different wheelchair models at multiple sites in LRS and RS. At least 5-10 users of each model should be enrolled for this data collection study. Measurements needed for corrosion and abrasion validation can be obtained during monthly maintenance of casters. This data can be collected during a prospective study to be conducted by UCP CLASP for the Google Wheelchair users' voice project[10] in Indonesia and Philippines. Failed samples encountered during the study should be saved for failure analysis in which factors contributing to failures can be evaluated.

It is anticipated that more data on caster failures will flow in through the caster failure checklist as ISWP plans to work with other organizations in setting up the provision of payments for doing the failure evaluations and reporting using the checklist. If some failure modes are found to be frequent, the research team will examine the failure evidence (photos and user comments) and make modifications to the protocol to simulate the failure.

In this study, a cascading approach was followed in which corrosion testing was followed by abrasion and shock testing. Based on the failure photos, it is recommended to follow a cyclic testing approach in which corrosion testing and abrasion + shock testing are conducted in a cyclic manner following a designated number of test cycles or time of exposure.

In addition to protocol upgrades and data collection, testing of casters based on conditions of use should be considered. Loads on the caster can be conditional on who uses the wheelchair (an adult or a child) similar to the ISO categorization of dummy weight for different sizes of wheelchairs. Additionally, the loads should be categorized based on the wheelbase length. Casters as shown on wheelchairs in Figure 4 will experience different loads with the same user weight. Based on earlier experimentation with WRR, GRIT and standard wheelchairs, the loads can be categorized as shown in Table 24 for users of manual wheelchairs. Loads in this table need to be modified based on load data collected on the example wheelchairs.

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[10] http://ucpwheels.org/google-org-ucp-wheels-for-humanity-align-to-bring-the-voice-of-wheelchair-users-forward/

Table 24. Categorization of loads on caster during testing

Caster placement on the wheelbase	**Caster beneath the wheelchair seat**	**Caster partially under the seat**	**Entire caster ahead of the wheelchair seat**	**Caster mounted on the cantilever**
Wheelchair examples	Motivation Active Folding Wheelchair, LDS Active Wheelchair	HKC, FWM Gen 2 and 3 wheelchairs	WRR, UCP Wheels Expression, LDS all-terrain wheelchair	GRIT, Motivation Moti-go, Motivation Rough Terrain wheelchair
Adult	35lbs	30lbs	25lbs	20lbs
Child	17.5lbs	15lbs	12.5lbs	10lbs

Testing protocol can be separated based on location of use of casters. If the manufacturer plans to test the casters for use in RS, corrosion and shock exposure testing can be conducted. For use in LRS and adverse environments, cyclic testing with shock + environmental factors should be conducted. All casters should be tested until fracture and plastic deformation failures. It takes maximum two to three days for casters to fail with the current validated protocol.

5.3 CASTER DESIGN RECOMMENDATIONS

Results from the preliminary and validated testing were used to develop the guidelines for design of caster parts (manual wheelchair only) shown in Table 25. These recommendations can be integrated into the ISWP Design Considerations document[11]. Manufacturers, designers, technicians and providers can refer to these recommendations for designing/selecting casters.

Table 25. Guidelines for design of manual wheelchair caster parts

Advantages	Disadvantages	Design Recommendations
Tire Hardness		
Softer tires (~70 A hardness) are able to absorb shocks better. Polyurethane material is light, low-cost and abrasion-resistant. Vulcanized rubber is durable with the right proportion of additives.	Hard tires (>75A hardness) are unable to absorb shocks and transfer them to the rest of the assembly and wheelchair. Polyurethane used for caster tires becomes loose when exposed to moisture and breaks down if exposed to heat and UV. Rubber material is heavy and may chalk out if it is low quality.	Softer tires are needed for a smoother ride in adverse conditions where the terrain is rough and rocky. Urethane casters are suitable for casters used in resourced areas with pavements. Proper adhesive should be used for tire bonding on the wheel. Care should be taken with material selection. The tire material should be compatible with the wheel material for bonding.

[11] http://www.wheelchairnet.org/ISWP/Resources/DesignConsiderations_WheelchairsAC_12142017.pdf

Table 25 (continued).

Tire Width		
Wider tires (>1.5in) are better when travelling on soft and rugged terrain. They can pass over gaps, such as subway grates. Narrow tires (<1in) are essentially performance tires that swivel without much effort on hard surfaces.	Wide tires may be heavier and require greater effort for turning. Narrow tires have poor tracking over soft and rugged terrain. They may not absorb shock easily if the tire is hard and thin which affects the strength of the caster.	Wider tires are best suited for use in adverse conditions however if the user does not have enough strength to maneuver and roll using these casters, narrow tires should be preferred. Performance tires that are used on active wheelchairs in LRS can range between 1in to 1.5in to leverage the capabilities of quick turning and rolling over rough and soft surfaces. Performance casters used in RS need to be narrower for faster turning and maneuvering.
Tire Bevel		
Conical shaped bevel assists in quicker turning as it requires less effort.	More effort is needed to turn with flat tires.	Wider tires require a conical shaped bevel so that they can be turned easily.
Tire Depth		
Tires with greater depth (>=1in) absorb shocks and will take a longer time to wear down.	Tires with less depth (<1in) are susceptible to caster wheel or axle bearing fractures since they cannot absorb shocks.	Use tires with greater depth for adverse conditions as they can last longer and absorb shocks.
Tire Tread		
Tread profile is present for caster to hold up and not slip on polished, wet surfaces.	Flat tread casters can slip easily on polished, wet surfaces.	If wheelchair is used indoors or in institutions, suitable tire tread is recommended.

Table 25 (continued).

Wheel/Tire Diameter		
Large size casters (>=6in) can roll easily over obstacles and have low rolling resistance. Shorter wheels (<4in.) are lightweight and less susceptible to flutter if shorter forks are used. They provide clearance for footrests.	Smaller size casters (<6in.) can get stuck in potholes and are unable to go over obstacles, street grates and stones. Heavy wheels can go into caster flutter easily. Caster wheel pockets for axle bearings can fracture during use if not tighter in tolerance. Bearings slip out because of this which can cause the assembly to fall apart.	In adverse conditions, beginners should use large size casters to go over obstacles, grass and gravel easily. More experienced and active users can use short size, wider casters as they can wheelie over obstacles easily. It is recommended to choose caster size after trying out the wheelchair outdoors with the client. Lightweight and durable casters are necessary to avoid flutter. Performance casters can employ aluminum wheels to reduce size and weight. For use in adverse conditions, caster wheel and spokes should be robust to avoid any fractures.
Fork Design		
Forks should have smoother corner bends at the prongs. Fork with thickness greater than 0.25in are averse to cracking and fracture. Height options for placement of the wheel on the forks enables clinicians and ATP find the optimal configuration for their client.	Forks with sharper corner bends can crack at the bend. Fork less than 0.25in thickness are known to crack and fracture with frequent shocks and impacts. Shorter trail size causes casters to flutter at high speeds. Large size wheels typically have smaller trails on the forks which can cause flutter.	Stronger forks with smoother bends are recommended for use in adverse conditions. Both steel and aluminum forks are suitable for RS. For adverse conditions, forks of medium strength steel are recommended. Height options are recommended. Usually three options are provided. Longer trail size (~2.5-3in.) is suggested to avoid caster flutter or shimmy. The longer trail should not hit the heels of the user.
Matching the fork width and axle assembly		

Table 25 (continued).

Tight tolerance between the axle bearings and fork prongs can keep the assembly intact.	Gap in the fork prongs and the axle bearings can create tolerance issues which can amplify during use. Forks are subjected to strain (can bend or crack) if the assembly is not tight.	There can be variation in the tolerances of parts when supplied in bulk. Appropriate supplier selection is important. Quality assurance at the supplier end is necessary.
Fork Coating		
Paints and coatings can keep away rust.	Galvanized or chromed forks are susceptible to rusting.	Use of suitable corrosion-resistant paint (usually black or blue) is suggested on forks.
Stem Bolt		
Stem bolts greater than or equal to ½in. can sustain impacts if made of medium strength steel.	Stem bolts less than ½ in diameter can fracture easily from impacts and fatigue. Stem bolts greater than or equal to ½in. can deform from shocks and impacts if poor quality steel is used.	For casters employed on wheelchairs used outdoors, stem bolts greater than or equal to 1/2in. are recommended. Medium or greater strength steels are recommended.
Axle Bolt		
Grade 8 or higher shoulder bolts that are greater than or equal to 5/16in diameter provide good durability and fatigue resistance.	Threaded bolts may lose threads as the forks hit on them. Shoulder length of the bolts should be appropriate. If not, the fork can eat up the threads and loosen the axle assembly.	Shoulder bolts of grade 8, greater than or equal to 5/16in. diameter and proper shoulder length are recommended.

Table 25 (continued).

Bearings		
Precision ground-sealed bearings like 6202/6202Z bearings are easier to find and replace. Suitable seals and shields can avoid corrosion of inner parts of the bearings. Bicycle ball bearings used as axle bearings are robust and have tighter tolerances.	Bearings with loose tolerances fall apart with shocks and impacts. There is significant variation in quality of bearings when supplied in bulk. Bicycle bearings require routine maintenance to remove any grass or yarns which can cause contamination. Corrosion can cause bearings to seize and contamination can make them sticky.	Bearings with high load bearing capacity and tight tolerances are required so that they do not loosen during use and fall apart. Supplier selection is important so that appropriate quality bearings are received every time. Bearings should be maintained to avoid issues caused by corrosion and contamination.

5.3.1 Caster selection considerations

There are multiple tradeoffs to be considered during selection of wheelchair casters. Involved in these tradeoffs are several factors including user's ability, conditions of use, product availability and serviceability in the region, cost, quality assurance and ease of installation and maintenance.

For instance, for novice wheelchair user, it may be difficult for them to navigate through stones and obstacles which an experienced user can do by performing a wheelie. Hence, for a novice user, it may be appropriate suitable to provide larger diameter wheels which can go over the rough terrain until they build their skills. If the outdoor surface conditions are uneven with gravel and stones, the user may require a wider tire. Increase width can provide more traction and easy roll when riding over rough surfaces. Narrower tires are best on smooth pavements, but they cannot turn when they get caught in obstacles. To determine the best combination of size, tire characteristics and maneuverability, it is recommended to try the casters in the user's home and outdoors and make a choice.

Bigger wheels with a larger trail can produce flutter at higher speeds. Flutter can begin with loose bearings and deformed parts at normal riding speeds also. To avoid shimmy and the associated risk of tipping the wheelchair during use, the user should be trained on use and maintenance of wheelchairs.

Locally produced parts are easily repairable, serviceable and available during replacement. The skateboard wheels used on certain wheelchair models in RS is an excellent example. They are less expensive, available in most shops in RS and can be easily maintained. Similarly, the Zimbabwe casters used on Whirlwind roughrider wheelchairs are suitable for local production because they use the standard bicycle hubs. Some caster models use the 6202/6202Z bearings which are typically available in LRS. The provider should be aware of the locally produced parts, and consider their cost, availability and serviceability when selecting the caster model.

Providers and users have to weigh the pros and cons of models during selection. For example, the Zimbabwe casters gather lot of hair and grass in the hub area among other casters. This causes obstruction to roll. The user should be trained about maintaining casters to avoid such issues.

Quality assurance of supplied caster parts is a must to avoid discrepancies in design and quality. Providers should ask for documentation regarding quality assurance or quality testing from suppliers. High-quality caster parts can cost more. Along with the aforementioned considerations, the provider will have to balance the funding available against caster parts' quality to make an appropriate selection.

5.4 WHEELCHAIR TESTING RECOMMENDATIONS

Inclusion of corrosion and abrasion testing factors in the testing protocol led to occurrence of caster failures commonly seen in the field. Rotating elements like stem bearings lost their performance and there are multiple movable, folding and swinging parts on the wheelchair like brakes, footrests and armrests which can be affected by corrosion exposure. Forks under strain fractured due to corrosion and it is possible that other wheelchair parts such as cross braces and back to seat connecting plates which are continuously under strain may suffer from corrosion. Tires have been a constant source of concern in LRS as they degrade faster on rough surfaces.

Wheelchair experts have noted wheelchair failures caused due to environmental factors in the product testing matrix (Table 4). Based on the significant effect of corrosion and abrasion on caster durability found in this study, testing wheelchairs and individual parts with these factors should be considered. For instance, wheelchairs can be corrosion tested prior to standards testing. Development of new test equipment and protocol may be necessary to include more testing factors.

The testing team at Free Wheelchair Mission has a new testing equipment[12] under development and they plan to test the entire wheelchair against shock and environmental factors. Four wheelchairs can be mounted on the test at once on a treadmill which includes slat patterns like the MDT and drops like CDT. The team later plans to deploy abrasive surfaces on the treadmill. Comparing results from such testing with MDT and CDT performance can aid the decision to include environmental factors into standard testing methods.

5.4.1 Corrosion evaluations

Corrosion alters the rolling resistance of bearings. There were different styles of bearings used in the caster testing study that were affected by corrosion to varying degrees. Some of them locked after corrosion testing. It is of interest to characterize the performance of bearings with and without corrosion to inform their selection by providers.

This study demonstrated that coating wheelchair parts like forks with suitable paints is necessary to avoid corrosion effects. During regular use, it is common for painting on the wheelchair frame to get scratched which can lead to rusting and then damage as was witnessed

[12] https://www.pr.com/press-release/713735

during this study. Another study recommendation is the evaluation of corrosion resistance of different paint materials and thickness of coatings. Outcomes from such study can enable the manufacturers and providers to select a suitable paint grade for wheelchairs.

5.5 DISSEMINATION AND IMPLEMENTATION

5.5.1 Disseminating standards information

Publication of the ISWP standards and related materials is in the works. There are a several ways in which ISWP plans to disseminate the standards:

- The ISO Technical Committee TC173 is aware of the standards work conducted by ISWP. Following suitable validation and testing, these standards will be published as
    - An addendum to existing suite of ISO 7176.
    - A separate standard.
    - A technical specification for immediate use of the testing method.

  The caster testing work carried out in this dissertation will be presented and discussed in the coming ISO meeting for publication.
- ISWP plans to disseminate manuals and materials including design, drawings, electrical schematics, operation and maintenance checklists for all the standards testing equipment through a Creative Commons license. Development of these materials is nearing

completion. They will be published on the ISWP[13] and ISWP Product List[14] websites under the Resources Hub.

- Caster design guidelines derived from caster testing and field data should be added to the Design Guidelines[15] published by ISWP.
- WHO, GATE and other international entities that advocate for high-quality wheelchairs should promote the implementation of ISWP standards through their policies and materials.
- One use of standards is allowing comparison and informing selection of products. This requires disclosure of testing information and results. Caster testing results will be published on the ISWP Product List soon under the product testing section.
- ISWP plans to work with manufacturers and organizations around the world to deploy testing equipment and develop testing sites.

5.5.2 Use and implementation of wheelchair standards in resourced settings

Wheelchair testing standards (ISO 7176) were published in the 1990's and since then, have been used in different ways. Regulatory agencies such as the Food and Drug Administration (FDA) and the Centre for Medicare and Medicaid Services (CMS) in the United States (US) have been referring to these standards to qualify products for marketing and sale. The Department of Veterans Affairs (VA) uses the standards testing results for wheelchair selection for prescription

[13] http://www.wheelchairnet.org/

[14] http://wheelprogress.org/

[15] http://www.wheelchairnet.org/ISWP/Resources/DesignConsiderations_WheelchairsAC_12142017.pdf

to veterans. Manufacturers and providers are also known to conduct in-home testing with new designs and quality testing for parts from new suppliers. In United Kingdom (UK), manufacturers perform such testing prior to applying to the Health Authority and launching their products with the CE mark. In certain accredited testing laboratories, products have been tested more than the minimum requirements i.e. until product failure. Design recommendations can be provided by such laboratories based on failure. Passing standards is also necessary for importing wheelchair products to other countries. While there are multiple applications, one should note that standards play an important role from a regulatory standpoint for qualifying wheelchairs.

Around the world, wheelchair standards are voluntary standards which means testing is not mandatory to qualifying wheelchair products through regulations. In the US, manufacturers can conduct testing on their own (like in the UK) and get clearances through FDA or the Consumer Protection Safety Commission (CPSC) to put their products on the market. Some motorized wheelchairs and scooters have followed the CPSC route for product clearances. This lax in the product qualification process does not guarantee that the product is high-quality and durable enough for outdoor use. This is reciprocated in the findings from wheelchair testing studies conducted over the last 20 years [69-80]. Multiple issues including failures with wheelchairs that are already available in the market have been reported. Wheelchair quality has stayed the same over the years [78].

The FDA and MHRA regulate products in US and UK respectively and manufacturers are required to do post-market surveillance once the device is on the market. Product recalls are done if there are consistent complaints about product performance or breakdown in the field. Causes for recalls and field issues can be identified, and the risk of adverse incidents minimized with standards testing and design evaluation through an accredited testing laboratory.

Recently, CMS has tightened the requirements for safety and performance testing of powered mobility devices. These tests need to be conducted at a RESNA-capable, independent testing facility. This is one step in the right direction. CMS can consider establishing similar requirements for durability testing – MDT and CDT and all testing procedures with manual wheelchairs through an independent testing facility. FDA and MHRA can consider appointing similar procedures for qualification.

5.5.3 Implementation of wheelchair standards in less-resourced settings

WHO Guidelines suggest multiple stakeholders including the governmental and non-governmental organizations, disabled people's organizations (DPO), aid agencies and manufacturers plan the implementation of standards. This suggestion is very broad, and it may take a while to execute it. In the meantime, WHO, USAID, ISWP and other foundations who are leading the charge for delivering appropriate wheelchairs can spread awareness about standards through their materials. WHO's recommendation on implementation comes a regulatory perspective though implementation can be done through a bottom-up approach as well. This can be achieved in two ways:

- Wheelchair service training packages developed by WHO in partnership with USAID and ISWP training materials lack information about standards. Test results are not informing wheelchair delivery. Training materials are intended for training professionals from clinical background like physical therapists, occupational therapists, clinicians, doctors, rehabilitation professionals, and personnel involved in managing wheelchair provision. If these people are unaware about the safety and durability of the product, and its usability in LRS, an appropriate wheelchair will not be delivered. Brief information on

ISO-7176 and ISWP standards testing and using testing results to compare and select products should be included in the training materials.

- Providers and DPOs in LRS who buy wheelchairs should be encouraged to request for testing information prior to purchasing products from manufacturers and suppliers. This will necessitate testing the same way testing is needed prior to importing wheelchairs.

To fully influence provision with standards, information on device test results should be available to providers, clinicians and clients. There are resources developed in RS to communicate the applicability of standards in clinical practice [138] and ISWP can build on this work and develop guidelines for application of new set of standards.

APPENDIX A

DEVELOPMENT OF WHEELCHAIR QUALITY STANDARDS FOR LESS--RESOURCED SETTINGS

Appendix A contains miscellaneous figures and tables from Chapter 1.0 .

Table A 1. WHO APL – manual wheelchair for active use (top-left), assistant control (top-right), with postural support (bottom-left), and electrically powered wheelchair (bottom-right) [57, 81]

Table A 2. ISWP-SWG member profiles.

Name	Professional position and current employer	Years of experience	Work themes and topics of interest related to wheelchairs
Daniel Martin	Engineer, Shonaquip (South Africa)	7	Design and development of wheelchairs and posture support devices for use in LRS.
Matt McCambridge	Instructor, Research Engineer, Massachusetts Institute of Technology (United States)	16	Design, design facilitation, testing and manufacturing of mobility and posture support devices for use globally, training of technical staff involved in the manufacturing and distribution of mobility and posture support devices.
Norman Reese	Associate Professor, LeTourneau University (United States)	7	Test and design improvements for LRS
Mark Sullivan (ISWP-SWG Chair)	Convaid (manufacturer of paediatric wheelchairs) and Polus Center (non-profit for prosthetics and wheelchair education and provision) (United States)	34	Product development of complex rehab wheelchairs for resourced countries. Wheelchair seating education in LRS.
Don Schoendorfer	Founder, Free Wheelchair Mission (United States)	17	Providing mobility to the poor with disabilities in LRS
Eric Wunderlich	Manager of Major Initiatives, LDS Church (United States)	12	Appropriate provision of wheelchairs in LRS
David Mahilo	Director Corporate Reliability, Invacare (United States)	25	Wheelchair standards development, wheelchair testing, product development
Chris Rushman	Technical Specialist, Motivation (United Kingdom)	22	Wheelchair product innovation, design and development, wheelchair production systems and production tooling design, wheelchair service training, technical training course or content design and development.

Table A 2 (continued).

Anand Mhatre	Graduate Student Researcher, University of Pittsburgh (United States)	4	Wheelchair standards development, wheelchair testing, product development
Jon Pearlman	Director, ISWP; Assistant Professor, University of Pittsburgh (United States)	15	Assistive technology transfer methods, design and development of products using participatory action design, wheelchair standards development and testing.

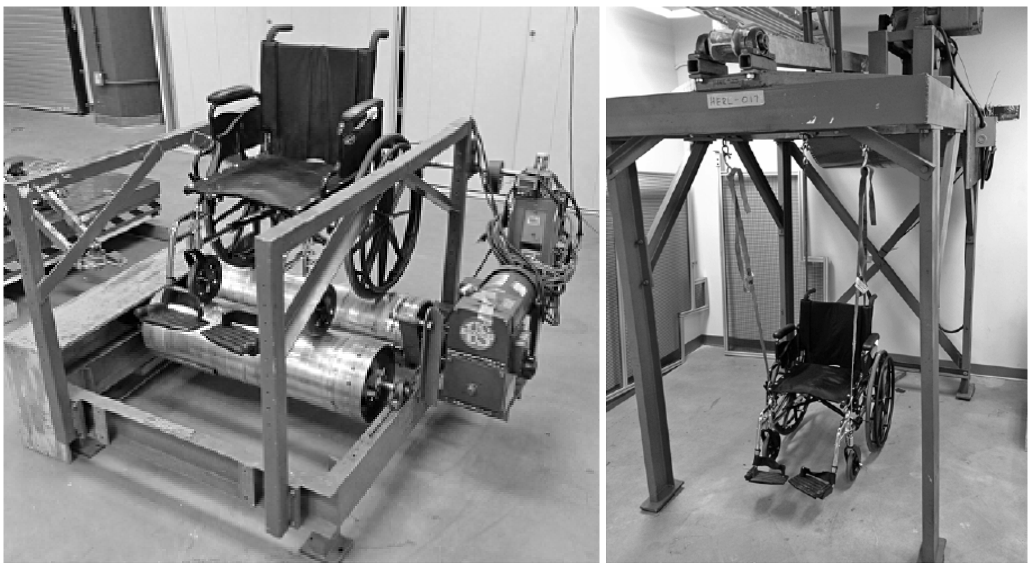


Figure A 1. MDT (left) and CDT (right) without test dummies [74]

APPENDIX B

A WHEELCHAIR CASTER TESTING SYSTEM AND PRELIMINARY TESTING OF CASTER MODELS

This Appendix contains miscellaneous materials from Chapter 2.0 .

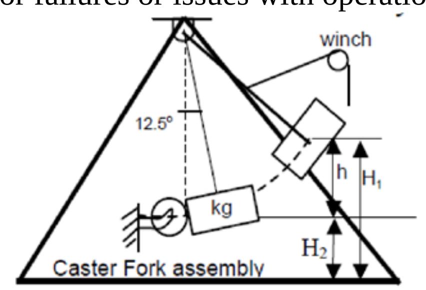
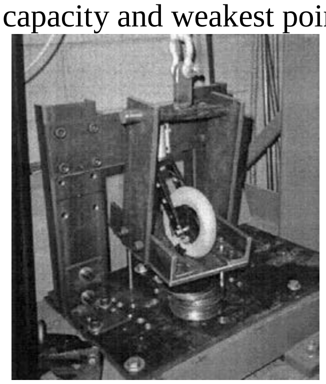
Table B 1. Caster Testing Subcommittee Members

Name	Professional position and current employer	Years of experience	Work themes and topics of interest related to wheelchairs
Daniel Martin	Engineer, Shonaquip (South Africa)	7	Design and development of wheelchairs and posture support devices for use in LRS.
Matt McCambridge	Instructor, Research Engineer, Massachusetts Institute of Technology (United States)	16	Design, design facilitation, testing and manufacturing of mobility and posture support devices for use globally, training of technical staff involved in the manufacturing and distribution of mobility and posture support devices.
Norman Reese	Associate Professor, LeTourneau University (United States)	7	Test and design improvements for LRS
Anand Mhatre	Graduate Student Researcher, University of Pittsburgh (United States)	4	Wheelchair standards development, wheelchair testing, product development

Table B 1 (continued).

Jon Pearlman	Director, ISWP; Assistant Professor, University of Pittsburgh (United States)	15	Assistive technology transfer methods, design and development of products using participatory action design, wheelchair standards development and testing.
Joseph Ott	Graduate Student Researcher, University of Pittsburgh (United States)	1	Wheelchair standards development, wheelchair testing, product development

Table B 2. Caster test methods reported in literature.

Study	Test Method
1. Curb impact testing [139]	Pendulum test: Hit the caster at 45 degree angle at 1m/s and check for failures or issues with operation. 
2. Evaluation of caster flutter[108]	Testing casters on treadmill and measure critical velocity (velocity above which flutter happens) for a set trail size for each caster.
3. Caster crash testing[140]	Casters are crash tested in a dynamic drop tester (see figure of the apparatus below) to determine the maximum load capacity and weakest point for failure. 

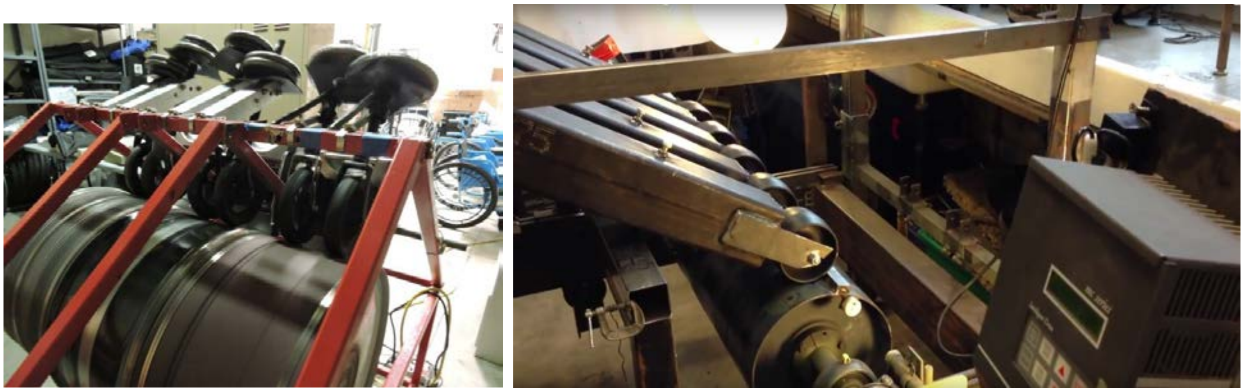


Figure B 1. Caster testing drum equipment with wheelchair manufacturers

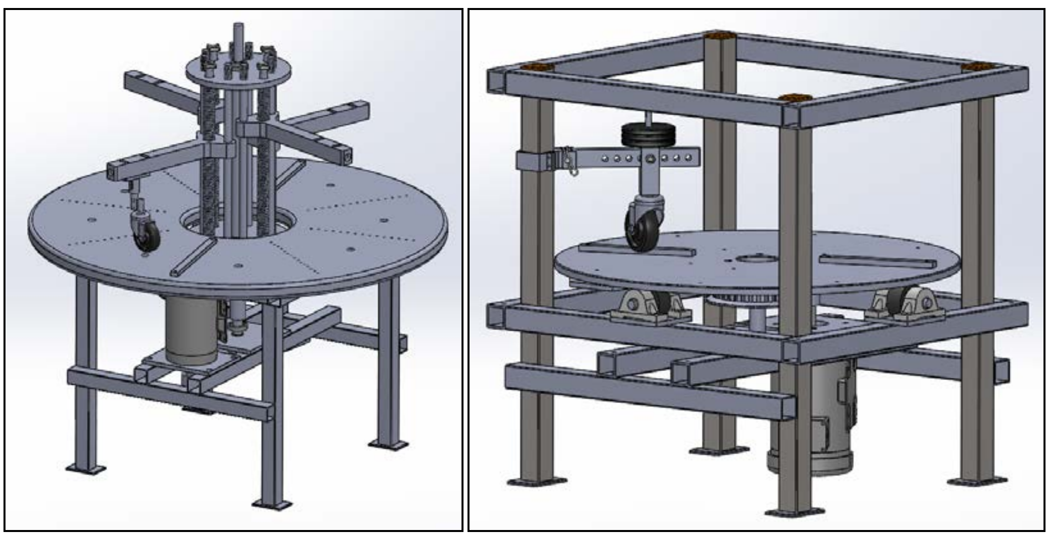


Figure B 2. Caster assembly test design concepts #4 (left) and #5 (right)

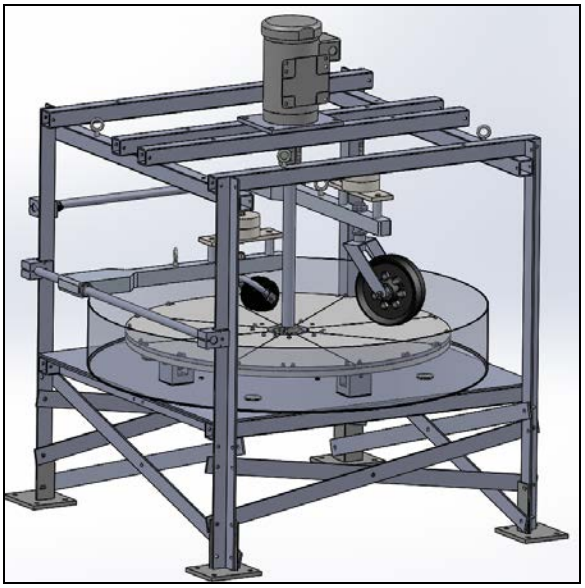


Figure B 3. Turntable design concept

Table B 3. Specifications of MDT and new caster testing equipment

Feature	**MDT**	**New Caster Assembly Test Design**
Speed	1m/s	1m/s
Test cycle	One rotation of the drum	One rotation of the turntable
Minimum number of test cycles	200,000	101,600 ≈ 100,000
Number of slat hits per revolution	1	2.02 ≈ 2
Weight on each caster	Varies between 19.5-35% for different wheelchairs	30% of the ISO 7176 Section 11 dummy weight = 30lbs
Nature of caster impacts	Casters are subjected to straight/vertical impacts from slats.	Casters will be subjected to straight/angular impacts.
Wheelbase length	Varies between 15-23 inches for wheelchairs.	The caster arm design allows for variable positioning on the turntable. Maximum length = 28 inches. Will not accommodate wheelbase length of three wheeled chairs.
Ability to change surface	Not applicable	The turntable is equipped with eight pie-shaped pieces, which can accommodate patterns that simulate different surface types.
Number of casters tested simultaneously	2	4

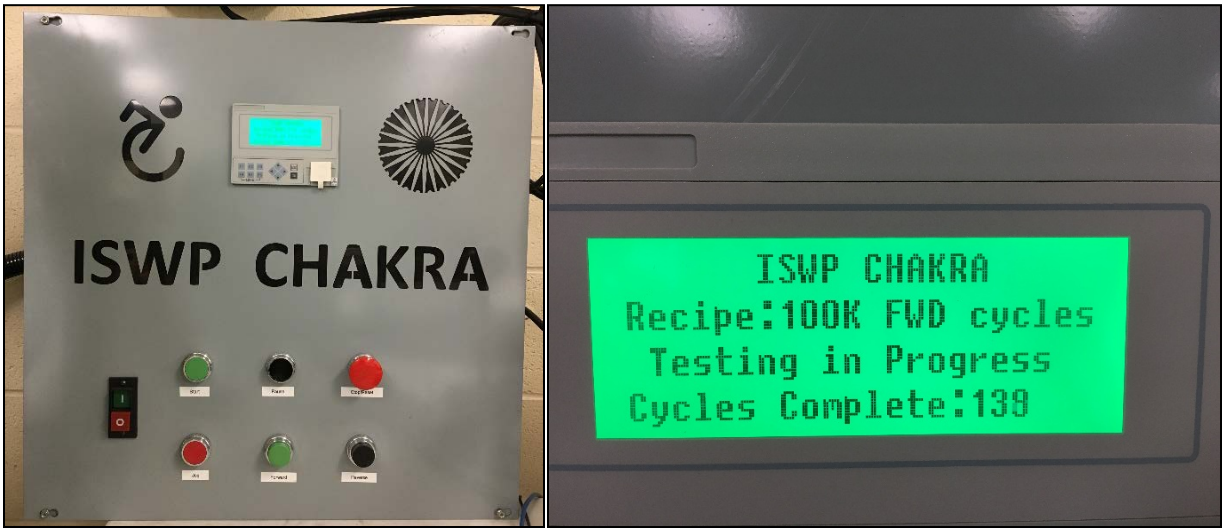


Figure B 4. Controller box of the caster test system (left) and LCD display (right)

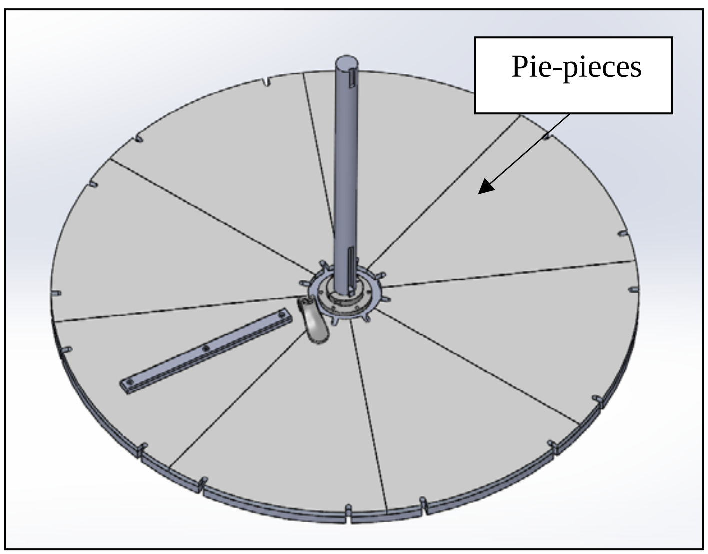


Figure B 5. Turntable Assembly with pie-pieces (only one slat mounted to pie-piece)

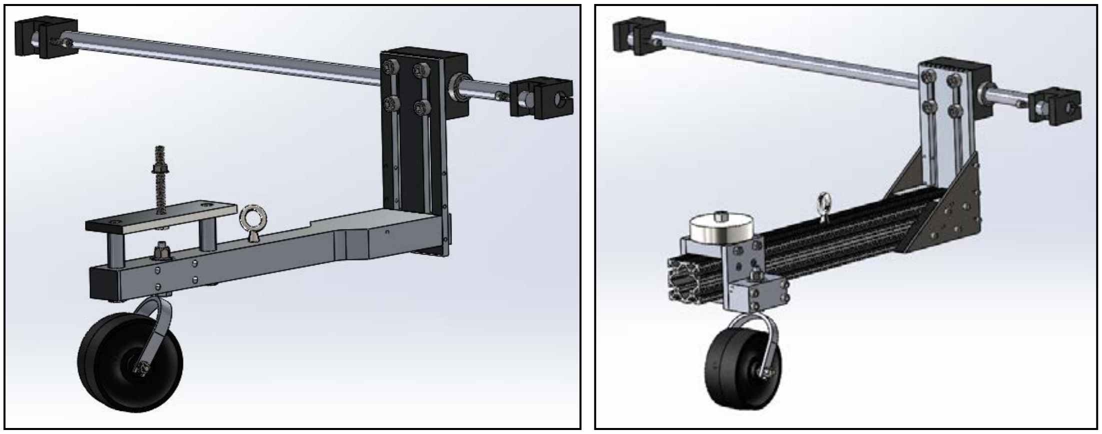
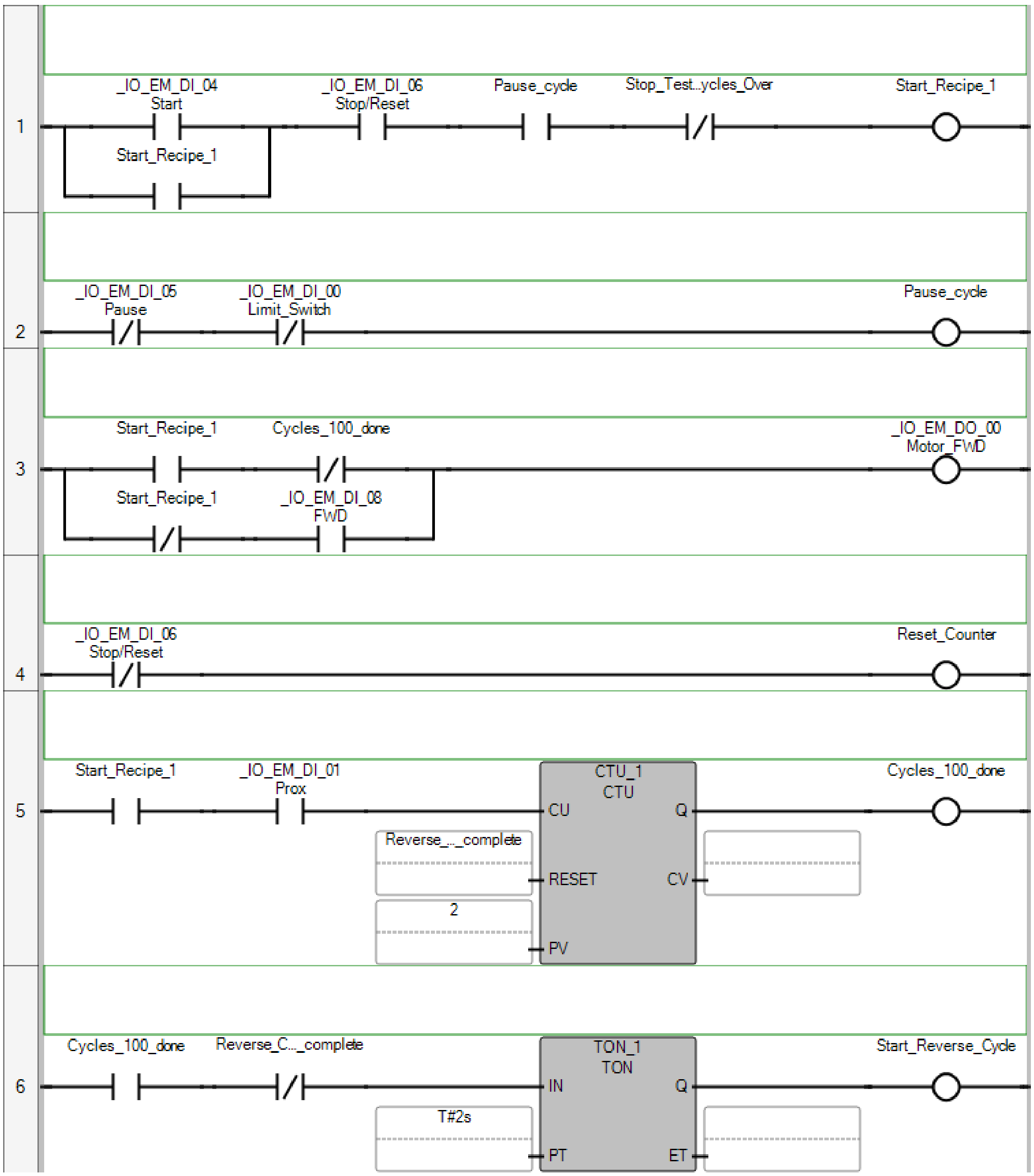


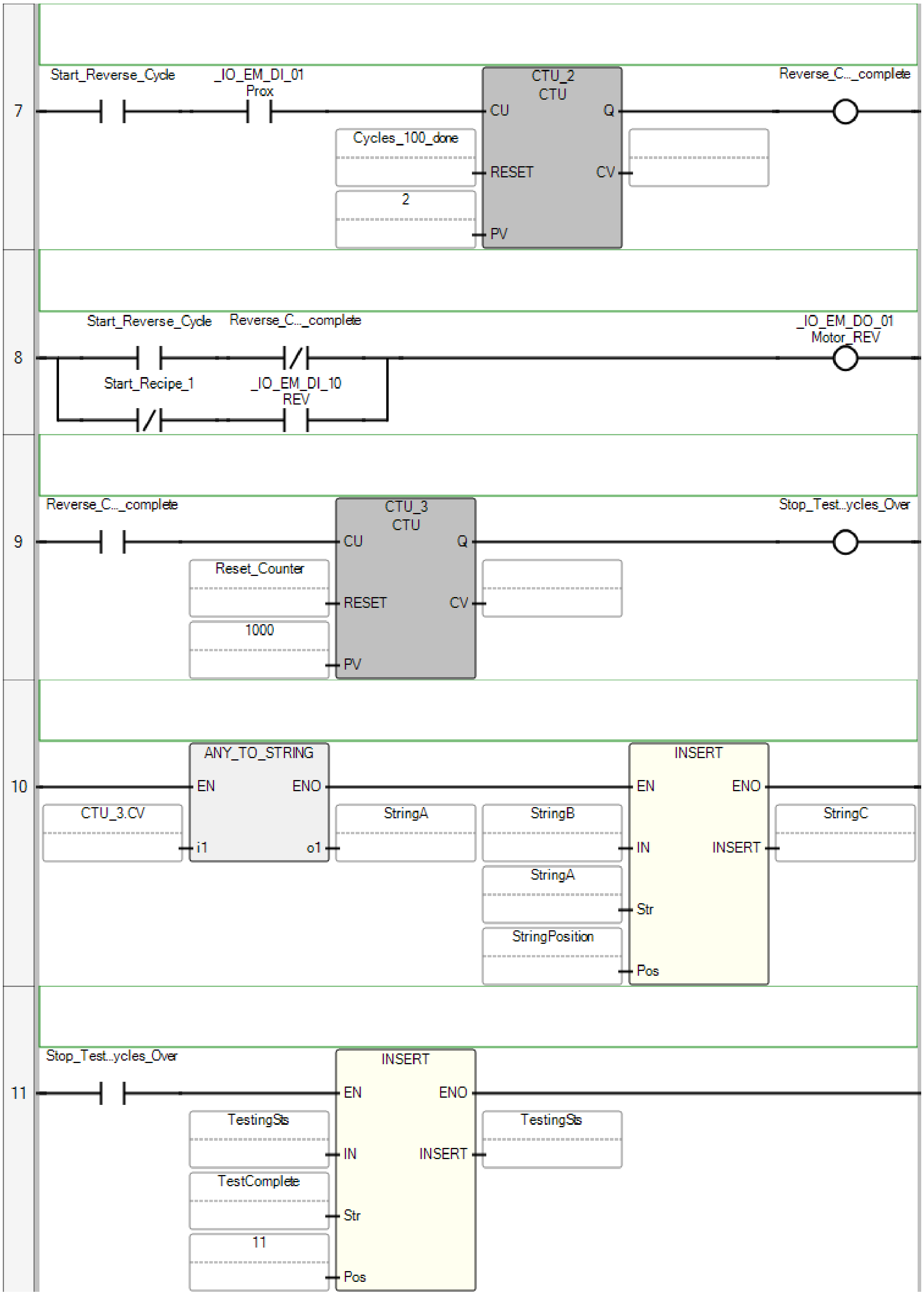
Figure B 6. Initial design (left) and revised design (right)

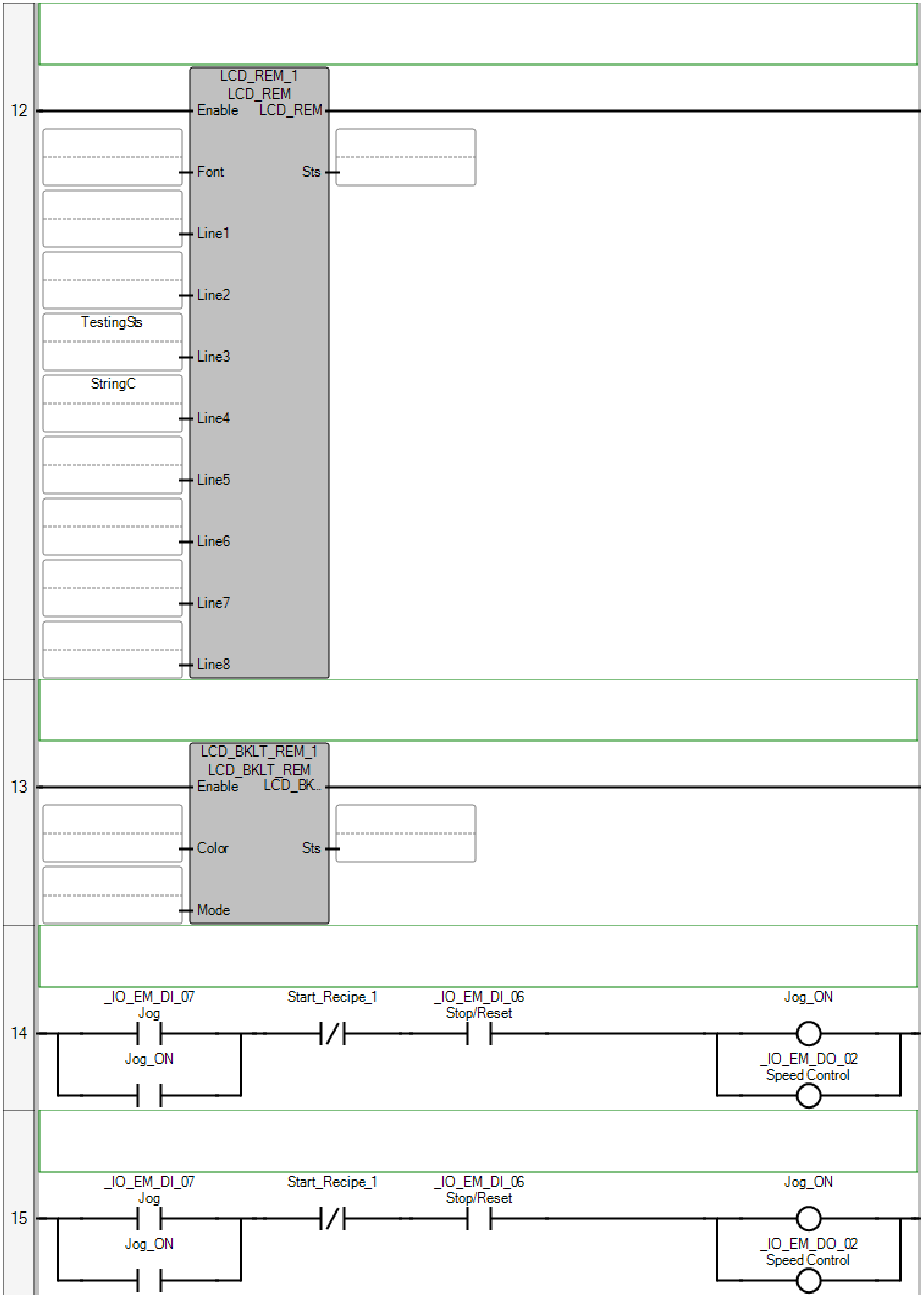
Table B 4. Results from feasibility testing of caster assemblies

Model	Slat Impact Angle (in degrees)	Number of Cycles Completed	Failures	Pictures of Failures
A	12±0.5	100,000	Slight play was noted in the stem bolt and bearings assembly.	NA
B	12±0.5	40,000	Stem bolt fractured and the crack initiated at an angle.	
C	12±0.5	100,000	Significant play was noted in the stem bolt and bearing assembly.	NA
D	0	35,000	Stem bolt fractured and the crack initiated straight in the direction of slat hit.	

B.1 CONTROLLER PROGRAMME FOR CONITNOUOUS FORWARD AND REVERSE MOTION




7
Start_Reverse_Cycle
_IO_EM_DI_01
Prox
CTU_2
CTU
CU
Q
Reverse_C..._complete
Cycles_100_done
RESET
CV
2
PV
8
Start_Reverse_Cycle
Reverse_C..._complete
_IO_EM_DO_01
Motor_REV
Start_Recipe_1
_IO_EM_DI_10
REV
9
Reverse_C..._complete
CTU_3
CTU
CU
Q
Stop_Test..ycles_Over
Reset_Counter
RESET
CV
1000
PV
10
ANY_TO_STRING
EN
ENO
INSERT
EN
ENO
CTU_3.CV
i1
o1
StringA
StringB
IN
INSERT
StringC
StringA
Str
StringPosition
Pos
11
Stop_Test..ycles_Over
INSERT
EN
ENO
TestingSts
IN
INSERT
TestingSts
TestComplete
Str
11
Pos


12
LCD_REM_1
LCD_REM
Enable
LCD_REM
Font
Sts
Line1
Line2
TestingSts
Line3
StringC
Line4
Line5
Line6
Line7
Line8
13
LCD_BKLT_REM_1
LCD_BKLT_REM
Enable
LCD_BK..
Color
Sts
Mode
14
_IO_EM_DI_07
Jog
Start_Recipe_1
_IO_EM_DI_06
Stop/Reset
Jog_ON
Jog_ON
_IO_EM_DO_02
Speed Control
15
_IO_EM_DI_07
Jog
Start_Recipe_1
_IO_EM_DI_06
Stop/Reset
Jog_ON
Jog_ON
_IO_EM_DO_02
Speed Control

The program defines 24 variable(s).

Variable Start_Recipe_1
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Stop_Test_Cycles_Over
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Test_Time
(* *)
Direction: Var
Data type: TIME
Attribute: Read/Write

Variable Timer_Start
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write
Variable Reset_Counter
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Jog_ON
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable CTD1_Done
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable NewVariable
(* *)
Direction: Var

Data type: STRING
Attribute: Read/Write

Variable CTU_1
(* *)
Direction: Var
Data type: CTU
Attribute: Read/Write

Variable Pause_cycle
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Cycles_100_done
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable TON_1
(* *)
Direction: Var
Data type: TON
Attribute: Read/Write

Variable Start_Reverse_Cycle
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable CTU_2
(* *)
Direction: Var
Data type: CTU
Attribute: Read/Write

Variable Reverse_Cycle_complete
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable CTU_3

(* *)
Direction: Var
Data type: CTU
Attribute: Read/Write

Variable LCD_REM_1
(* *)
Direction: Var
Data type: LCD_REM
Attribute: Read/Write

Variable LCD_BKLT_REM_1
(* *)
Direction: Var
Data type: LCD_BKLT_REM
Attribute: Read/Write

Variable StringB
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable StringPosition
(* *)
Direction: Var
Data type: DINT
Attribute: Read/Write

Variable StringC
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable StringA
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable TestingSts
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable TestComplete
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

APPENDIX C

DEVELOPMENT AND PSYCHOMETRIC EVALUATION OF THE CASTER FAILURE CHECKLIST

Table C 1. Failure items chosen for checklist

Caster Part	Failure Modes
1. Stem Bolt	1. Fracture
2. Stem Bearings	1. Corrosion 2. Loose 3. Contamination
3. Fork	1. Bent 2. Fracture 3. Paint Chipping 4. Corrosion
4. Axle Bolt	1. Fracture 2. Corrosion
5. Axle Bearings	1. Corrosion 2. Loose 3. Contamination 4. Loose contact with the wheel 5. Trueness 6. Rollability
6. Wheel	1. Fracture or broken spoke 2. Corrosion
7. Tire	1. Worn-out Tire 2. Worn-out tread 3. Etching 4. Pitting 5. Cracking 6. Deflated

Table C 1 (continued).

8. Fasteners	1. Corrosion 2. Loose

Table C 2. Casters used in the test-retest study

Number	Wheelchair/Caster Model	Failure Pictures
1	Panthera	
2	Invacare Action 3G	
3	Free Wheelchair Mission Polyurethane Caster	
4	Hopehaven Kids Chair	
5	Free Wheelchair Mission Rubber Caster	

Table C 2 (continued).

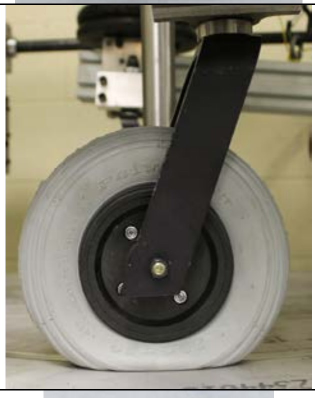
6	Invacare Action 3NG	
7	NextHealth Caster	
8	Primo Caster	
9	Free Wheelchair Mission Rubber Caster	
10	Invacare Standard	

Table C 2 (continued).

11	Invacare Spectra Plus	
12	Hopehaven Kids Chair	
13	Invacare Action 4NG	
14	Hopehaven Kids Chair	

Table C 2 (continued).

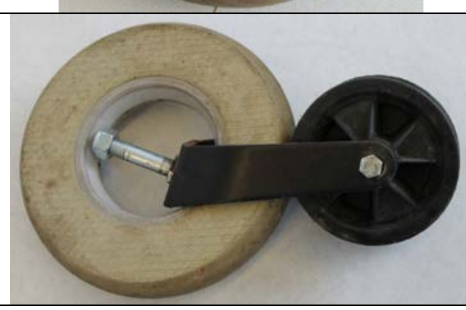
15	Motivation Rough Terrain	
16	Whirlwind Roughrider	
17	Primo Caster	
18	Invacare Action 3G	
19	Inavacare Mirage	

Table C 2 (continued).

20	Free Wheelchair Mission Rubber Caster	
21	Inavacare Action 2G	
22	Primo Caster	
23	LDS Charities Standard Chair	
24	Free Wheelchair Mission Polyurethane Caster	

Table C 2 (continued).

25	UCP Expression Wheelchair	
26	Free Wheelchair Mission Polyurethane Caster	
27	Whirlwind Roughrider	
28	Free Wheelchair Mission Rubber Caster	

C.1 EXPERT REVIEW OF CHECKLIST ITEMS

Introduction – Caster Failure Checklist

Wheelchair caster failure is a serious issue as per research and anecdotal evidence. Caster failures that are observed during field use and standards testing are diverse in nature. Stem bolts break, bearings corrode, tires degrade and crack and so on. When it comes to rough terrains and tropical conditions in less-resourced environments, casters are known to fail prematurely which can cause injury to user or wheelchair to breakdown.

As researchers, we would like to evaluate and understand failures so that we can develop robust designs that are durable, require less maintenance and incur fewer repairs. Failures are classified during standards testing on wheelchairs as Class I, II and III based on the nature of failure and resources required to repair the failure. But such classification is not applicable to assess and compare the different failure modes for casters. We require some means or a tool to evaluate failures in a reliable manner. With this motivation, we are developing a comprehensive checklist that can be used by wheelchair experts to evaluate caster failures. After development, we aim to use this checklist to correlate failures from lab-based standard tests and outdoor use. Casters will be evaluated physically or through photographs.

The checklist initially presents anatomy of a typical caster for reference to the expert. Parts from different manufacturers have design variations and hence examples of such parts have been included as well. Further, the checklist lists failure modes observed with different parts of the caster. These failures were extracted from the product testing matrix that was developed from our working group discussion last year. Experts will be evaluating a used caster against the different failure modes.

As a part of developing this checklist, we request your feedback on the failures included in this checklist through a survey below. We would like to know whether failures mentioned in the checklist:

(a) should be included.

(b) can cause injury to the user.

(c) can damage other caster parts or to the wheelchair leading to breakdown.

As a reviewer, we are asking you to rate each failure item against the aforementioned criteria. In case you have comments or suggestions on a particular question, do write them in the comment boxes following the review of failure items.

Anatomy of a typical caster assembly

A typical caster contains the following parts:

1. Axle Bolt
2. Axle Bearings
3. Wheel
4. Tire
5. Stem Bearings
6. Stem Bolt
7. Fork

A caster model with parts mentioned above is as follows:

Caster parts from different manufacturers have design variations and following sections include information on different caster part designs and examples.

Information on Parts 1 - Axle Bolt and 6 - Stem Bolt

Parts #1 and #6 are simply bolts; in most models axle bolts act as axles or shafts for the caster wheel.

Information on Part 2 - Axle Bearings

Axle bearings (Part #2) are can be sealed or unsealed. They are of different types - roller bearings and bicycle axle and bearing set as shown below.

1. Sealed Roller Bearings

2. Bicycle axle and bearing set

3. Bicycle axle and bearing set (spoke flanges removed)

<u>Information on Part 3 - Caster Wheel</u>

Caster wheels (Part #3) vary in styles for each model among different manufacturers. They are made of plastic or steel. Following are some designs of caster wheel:

1. Solid wheels

2. Spoked Wheels

3. Alternate designed wheels

<u>Information on Part 4 - Tire</u>

Tires (Part #4) are made of rubber or polyurethane. They can be solid or pneumatic. They have a range of profiles-- some have treads, some are flat, and others have a slight angle or pitch to them. Following are some pictures of different tire tread types.

1. Straight tire tread:

2. Flat tire tread:

3. Angled Tread Design:

Information on Part 5 - Stem Bearings

Stem Bearing (Part#5) types include sealed roller bearings (as shown in Part#2) and flanged bearings as shown below.

Information on Part 7 - Fork

Forks (Part #7) differ from model to model and the pictures below show different types of forks used on wheelchair casters. The two prongs on the fork are usually welded to an assembly that holds the stem bolt and bearings.

Review Checklist Items

The following checklist contains a list of failures that are known to occur with wheelchair casters. Please review each failure item listed below and answer whether the item should be included in the checklist.

2.1 Part 2: Axle Bearing
Failure Mode: Corrosion

Illustrations:

2.1a Review failure item - axle bearing corrosion

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

2.1b Rate the likely consequence(s) associated with this failure item - axle bearing corrosion

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

2.2 Part 2: Axle Bearing
Failure Mode: Obstruction to rolling

Illustrations:

2.2a Review failure item - axle bearing's obstruction to rolling

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

2.2b Rate the likely consequence(s) associated with this failure item - axle bearing's obstruction to rolling

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

2.3 Part 2: Axle Bearing
Failure Mode: Fracture

Illustrations:

2.3a Review failure item - axle bearing fracture

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

2.3b Rate the likely consequence(s) associated with this failure item - axle bearing fracture

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

3.1 Part 3: Caster Wheel
Failure Mode: Fracture

Illustrations:

3.1a Review failure item - caster wheel fracture

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

3.1b Rate the likely consequence(s) associated with this failure item - caster wheel fracture

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

3.2 Part 3: Caster Wheel
Failure Mode: Corrosion

Illustrations:

3.2a Review failure item - caster wheel corrosion

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

3.2b Rate the likely consequence(s) associated with this failure item - caster wheel corrosion

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

4.1 Part 4: Tire
Failure Mode: Tread Worn Out

Illustrations:

4.1a Review failure item - tire tread worn out

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

4.1b Rate the likely consequence(s) associated with this failure item - tire tread worn out

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

4.2 Part 4: Tire
Failure Mode: Worn Out

Illustrations:

4.2a Review failure item - tire worn out

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

4.2b Rate risks associated with failure item - tire worn out

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

4.3 Part 4: Tire
Failure Mode: Cracking

Illustrations:

4.3a Review failure item - tire cracking

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

4.3b Rate the likely consequence(s) associated with this failure item - tire cracking

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

4.4 Part 4: Tire
Failure Mode: Deflated tire

Illustrations:

4.4a Review failure item - deflated tire

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

4.4b Rate the likely consequence(s) associated with this failure item - deflated tire

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

5.1 Part 5: Stem Bearings
Failure Mode: Corrosion

Illustrations:

5.1a Review failure item - stem bearings corrosion

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

5.1b Rate the likely consequence(s) associated with this failure item - stem bearings corrosion

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

6.1 Part 6: Stem Bolt
Failure Mode: Fracture

Illustrations:

6.1a Review failure item - stem bolt fracture

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

6.1b Rate the likely consequence(s) associated with this failure item - stem bolt fracture

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

7.1 Part 7: Fork
Failure Mode: Bent fork

Illustrations:

7.1a Review failure item - bent fork

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

7.1b Rate the likely consequence(s) associated with this failure item - bent fork

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

7.2 Part 7: Fork
Failure Mode: Fracture

Illustrations:

7.2a Review failure item - fork fracture

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

7.2b Rate the likely consequence(s) associated with this failure item - fork fracture

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

7.3 Part 7: Fork
Failure Mode: Corrosion

Illustrations:

7.3a Review failure item - fork corrosion

	Yes (1)	No (2)
Include failure item in checklist (1)	O	O

7.3b Rate the likely consequence(s) associated with this failure item - fork corrosion

	High (1)	Medium (2)	Low (3)	No risk (4)
Risk of Injury to the wheelchair user (1)	O	O	O	O
Risk of damage to other parts of the wheelchair (2)	O	O	O	O

Questions:

Please suggest other failures seen with the caster assemblies that you would like to include in the checklist.

Suggested failures for Part#1: Axle Bolt

____

Suggested failures for Part#2: Axle Bearings

____

Suggested failures for Part#3: Wheel

____

Suggested failures for Part#4: Tire

____

Suggested failures for Part#5: Stem Bearings

____

Suggested failures for Part#6: Stem Bolt

____

Suggested failures for Part#7: Fork

____

Provide an overall feedback about the checklist items and any other comments you may have.

____

C.2 INSTRUCTIONS TO EVALUATE CASTER FAILURES

Following are picture illustrations and instructions on inspection of caster failures.

Part 2: Axle Bearing
Failure Mode: Corrosion
Instructions: Inspect for rust on the axle bearing.
Illustrations:

Failure Mode: Obstruction to rolling
Instructions: Roll the caster wheel and check for any resistance to rolling. Inspect for presence of strings or hair between the fork and bearings that can cause such obstruction.
Illustrations:

Failure Mode: Fracture
Instructions: Check for broken bearings.
Illustrations:

Part 3: Caster Wheel
Failure Mode: Fracture

Instructions: Inspect the wheel and spokes for any evidence of cracking or breakage.
Illustrations:

Part 4: Tire

Failure Mode: Roll-off
Instructions: Check if the tire has rolled-off the caster wheel.
Illustrations:

Failure Mode: Worn Out
Instructions: Inspect for presence of tire material on the wheel of the caster.
Illustrations:

Failure Mode: Etching or Cracking

Instructions: Inspect for cracked or etched (on sides) tire.
Illustrations:


Failure Mode: Deflated tire
Instructions: Inspect for deflated tire
Illustrations:

Part 5: Stem Bearings

Failure Mode: Fracture
Instructions: Inspect the stem bearings for fractures.
Illustrations:

Failure Mode: Corrosion

Instructions: Inspect the stem bearing assembly for corrosion
Illustrations:



Part 6: Stem Bolt

Failure Mode: Fracture
Instructions: Inspect for cracking or broken stem bolt.
Illustrations:

Part 7: Fork

Failure Mode: Bent fork
Instructions: Inspect if the fork is bent.
Illustrations:

Failure Mode: Fracture

Instructions: Inspect if the fork is broken or cracked.
Illustrations:


Failure Mode: Corrosion
Instructions: Inspect the fork for any corrosion.
Illustrations:

C.3 CASTER FAILURE CHECKLIST

Failure mode	Failure present	Failure not present	Unable to evaluate
Axle Bearing Corrosion	○	○	○
Axle Bearing Obstruction to Rolling	○	○	○
Axle Bearing Fracture	○	○	○
Caster Wheel Fracture	○	○	○
Tire Roll-off	○	○	○
Tire Worn-out	○	○	○
Tire Cracking	○	○	○
Deflated Tire	○	○	○
Stem Bearing Fracture	○	○	○
Stem Bearing Corrosion	○	○	○
Stem Bolt Fracture	○	○	○
Bent Fork	○	○	○
Fork Fracture	○	○	○
Fork Corrosion	○	○	○

C.4 TEST-RETEST RELIABILITIES FOR PARTICPANTS IN PHYSICAL EVALUATION GROUPPARTICIPANT 1 TEST-RETEST RELIABILITY

Participant 1 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.933	0.066	96.42857	0	0
Axle bearing's obstruction to rolling	0.668	0.179	82.14286	0	2
Axle bearing fracture	0.694	0.14	85.71429	0	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	1	0	96.42857	0	1
Tire worn out	0.627	0.242	92.85714	0	0
Tire cracking	0.81	0.129	92.85714	0	0
Deflated tire	1	0	100	0	0
Stem bearing fracture	0.881	0.08	92.85714	0	0
Stem bearing corrosion	1	0	100	0	0
Stem bolt fracture	0.933	0.065	92.85714	0	1
Bent fork	0.932	0.66	96.42857	0	0
Fork fracture	0.935	0.063	92.85714	0	1
Fork corrosion	0.944	0.055	92.85714	0	1

Participant 2 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.87	0.086	92.85714	0	0
Axle bearing's obstruction to rolling	0.891	0.107	96.42857	0	0
Axle bearing fracture	0.821	0.121	92.85714	0	0
Caster wheel fracture	0.711	0.188	92.85714	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.929	0.07	96.42857	0	0
Tire cracking	0.909	0.089	96.42857	0	0
Deflated tire	0.781	0.21	96.42857	0	0
Stem bearing fracture	0.617	0.119	75	0	0
Stem bearing corrosion	0.838	0.087	89.28571	0	0
Stem bolt fracture	0.665	0.12	78.57143	0	0
Bent fork	0.932	0.066	96.42857	0	0
Fork fracture	0.939	0.059	96.42857	0	0
Fork corrosion	1	0	100	0	0

Participant 3 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.879	0.08	92.85714	0	0
Axle bearing's obstruction to rolling	1	0	100	0	0
Axle bearing fracture	0.669	0.171	89.28571	0	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	0.781	0.21	96.42857	0	0
Tire worn out	0.708	0.194	92.85714	0	0
Tire cracking	0.602	0.159	82.14286	0.001	0
Deflated tire	0.65	0.322	96.42857	0	0
Stem bearing fracture	0.661	0.117	78.57143	0	0
Stem bearing corrosion	0.888	0.077	92.85714	0	0
Stem bolt fracture	0.712	0.114	82.14286	0	0
Bent fork	0.855	0.096	92.85714	0	0
Fork fracture	0.816	0.099	85.71429	0	1
Fork corrosion	0.892	0.073	92.85714	0	0

Participant 4 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.928	0.068	92.85714	0	1
Axle bearing's obstruction to rolling	0.137	0.161	53.57143	0.318	0
Axle bearing fracture	0.217	0.19	71.42857	0.102	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	0.843	0.153	96.42857	0	0
Tire worn out	0.65	0.322	96.42857	0	0
Tire cracking	0.761	0.129	89.28571	0	0
Deflated tire	0.843	0.153	96.42857	0	0
Stem bearing fracture	0.65	0.122	78.57143	0	0
Stem bearing corrosion	0.73	0.106	82.14286	0	0
Stem bolt fracture	0.821	0.096	89.28571	0	0
Bent fork	0.724	0.118	85.71429	0	0
Fork fracture	0.87	0.088	92.85714	0	0
Fork corrosion	0.889	0.075	89.28571	0	1

Participant 5 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.869	0.088	92.85714	0	0
Axle bearing's obstruction to rolling	0.768	0.156	92.85714	0	0
Axle bearing fracture	0.698	0.151	89.28571	0	0
Caster wheel fracture	0.837	0.158	96.42857	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.462	0.322	92.85714	0.015	0
Tire cracking	0.9	0.98	96.42857	0	0
Deflated tire	0.65	0.322	96.42857	0	0
Stem bearing fracture	0.775	0.101	85.71429	0	0
Stem bearing corrosion	0.945	0.054	96.42857	0	0
Stem bolt fracture	0.878	0.084	92.85714	0	0
Bent fork	1	0	100	0	0
Fork fracture	1	0	100	0	0
Fork corrosion	0.717	0.105	82.14286	0	0

Participant 6 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.566	0.115	71.42857	0	0
Axle bearing's obstruction to rolling	0.381	0.138	64.28571	0.006	0
Axle bearing fracture	0.186	0.12	64.28571	0.09	0
Caster wheel fracture	0.717	0.185	92.85714	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.778	0.12	85.71429	0	1
Tire cracking	0.825	0.119	92.85714	0	0
Deflated tire	0.65	0.322	96.42857	0	0
Stem bearing fracture	0.592	0.128	75	0	0
Stem bearing corrosion	0.835	0.09	89.28571	0	0
Stem bolt fracture	0.939	0.059	96.42857	0	0
Bent fork	0.93	0.067	92.85714	0	1
Fork fracture	0.936	0.062	96.42857	0	0
Fork corrosion	0.946	0.053	96.42857	0	0

Participant 7 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.946	0.053	78.57143	0	0
Axle bearing's obstruction to rolling	0.798	0.11	85.71429	0	1
Axle bearing fracture	0.415	0.181	75	0.004	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	0.781	0.21	96.42857	0	0
Tire worn out	0.85	0.102	92.85714	0	0
Tire cracking	0.56	0.167	82.14286	0.001	0
Deflated tire	0.242	0.201	78.57143	0.038	1
Stem bearing fracture	0.668	0.116	78.57143	0	0
Stem bearing corrosion	0.946	0.053	96.42857	0	0
Stem bolt fracture	0.657	0.119	78.57143	0	0
Bent fork	0.926	0.071	96.42857	0	0
Fork fracture	1	0	100	0	0
Fork corrosion	0.944	0.054	92.85714	0	1

Participant 8 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.809	0.1	89.28571	0	0
Axle bearing's obstruction to rolling	0.743	0.138	89.28571	0	0
Axle bearing fracture	0.904	0.095	96.42857	0	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	0.781	0.21	96.42857	0	0
Tire worn out	0.574	0.153	78.57143	0.002	0
Tire cracking	0.55	0.154	75	0.003	1
Deflated tire	0.537	0.22	85.71429	0	1
Stem bearing fracture	0.78	0.101	85.71429	0	0
Stem bearing corrosion	0.71	0.116	78.57143	0	1
Stem bolt fracture	0.88	0.081	92.85714	0	0
Bent fork	0.779	0.12	89.28571	0	0
Fork fracture	0.821	0.098	89.28571	0	0
Fork corrosion	0.884	0.078	85.71429	0	2

Participant 9 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.558	0.129	71.42857	0	0
Axle bearing's obstruction to rolling	0.62	0.139	82.14286	0	0
Axle bearing fracture	0.126	0.064	32.14286	0.054	0
Caster wheel fracture	0.65	0.322	96.42857	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.887	0.11	96.42857	0	0
Tire cracking	1	0	100	0	0
Deflated tire	1	0	100	0	0
Stem bearing fracture	0.561	0.145	75	0	0
Stem bearing corrosion	0.721	0.113	82.14286	0	0
Stem bolt fracture	0.814	0.1	89.28571	0	0
Bent fork	0.93	0.69	96.42857	0	0
Fork fracture	1	0	100	0	0
Fork corrosion	1	0	100	0	0

Participant 10 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	1	0	100	0	0
Axle bearing's obstruction to rolling	0.41	0.156	75	0.007	0
Axle bearing fracture	0.113	0.19	71.42857	0.437	1
Caster wheel fracture	1	0	96.42857	0	1
Tire roll-off	0.781	0.21	96.42857	0	0
Tire worn out	0.62	0.153	82.14286	0	0
Tire cracking	0.825	0.119	92.85714	0	0
Deflated tire	1	0	96.42857	0	1
Stem bearing fracture	0.352	0.225	82.14286	0.039	0
Stem bearing corrosion	0.481	0.153	75	0.003	0
Stem bolt fracture	0.84	0.153	96.42857	0	0
Bent fork	0 (24/28)	NA	85.71429	NA	0
Fork fracture	0.52	0.238	89.28571	0.002	0
Fork corrosion	0.841	0.105	92.85714	0	0

Participant 11 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.558	0.119	71.42857	0	0
Axle bearing's obstruction to rolling	0.185	0.142	50	0.167	0
Axle bearing fracture	0.274	0.174	60.71429	0.09	0
Caster wheel fracture	0.453	0.166	78.57143	0	0
Tire roll-off	0.781	0.21	96.42857	0	0
Tire worn out	0.505	0.159	75	0.006	0
Tire cracking	0.49	0.163	75	0.008	0
Deflated tire	0.404	0.138	67.85714	0.003	0
Stem bearing fracture	0.25	0.139	50	0.068	1
Stem bearing corrosion	0.533	0.113	67.85714	0	0
Stem bolt fracture	0.517	0.137	71.42857	0	0
Bent fork	0.772	0.124	89.28571	0	0
Fork fracture	0.742	0.119	82.14286	0	1
Fork corrosion	0.674	0.116	78.57143	0	0

Participant 12 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.932	0.067	96.42857	0	0
Axle bearing's obstruction to rolling	0.636	0.158	85.71429	0	0
Axle bearing fracture	0.78	0.134	92.85714	0	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	0.781	0.21	96.42857	0	0
Tire worn out	0.652	0.157	85.71429	0	0
Tire cracking	0.375	0.198	82.14286	0.11	0
Deflated tire	1	0	100	0	0
Stem bearing fracture	0.83	0.092	89.28571	0	0
Stem bearing corrosion	0.839	0.087	89.28571	0	0
Stem bolt fracture	0.939	0.059	96.42857	0	0
Bent fork	0.936	0.071	96.42857	0	0
Fork fracture	1	0	100	0	0
Fork corrosion	0.837	0.087	89.28571	0	0

C.5 TEST-RETEST RELIABILITIES FOR PARTICPANTS IN ONLINE EVALUATION GROUP

Participant 1 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.377	0.102	53.57143	0	0
Axle bearing's obstruction to rolling	0.142	0.079	39.28571	0.055	0
Axle bearing fracture	0.039	0.029	25	0.454	0
Caster wheel fracture	0.684	0.166	89.28571	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.716	0.184	92.85714	0	0
Tire cracking	0.547	0.185	85.71429	0	0
Deflated tire	0.785	0.204	96.42857	0	0
Stem bearing fracture	-0.006	0.14	53.57143	0.959	0
Stem bearing corrosion	0.33	0.162	64.28571	0.012	0
Stem bolt fracture	0.423	0.15	67.85714	0.001	0
Bent fork	0.035	0.109	46.42857	0.418	0
Fork fracture	0.184	0.121	46.42857	0.032	0
Fork corrosion	0.616	0.125	75	0	0

Participant 2 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.606	0.131	75	0	0
Axle bearing's obstruction to rolling	0.727	0.126	85.71428571	0	0
Axle bearing fracture	0.419	0.217	67.85714286	0.003	0
Caster wheel fracture	0.538	0.222	89.28571429	0	0
Tire roll-off	0.58	0.184	89.28571429	0	0
Tire worn out	0.641	0.226	92.85714286	0	0
Tire cracking	0.53	0.173	82.14285714	0	0
Deflated tire	0.785	0.204	96.42857143	0	0
Stem bearing fracture	0.319	0.174	67.85714286	0.04	0
Stem bearing corrosion	0.337	0.17	67.85714286	0.019	0
Stem bolt fracture	0.751	0.114	85.71428571	0	0
Bent fork	0.93	0.069	96.42857143	0	0
Fork fracture	0.821	0.098	89.28571429	0	0
Fork corrosion	0.942	0.057	96.42857143	0	0

Participant 3 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.908	0.09	96.42857	0	1
Axle bearing's obstruction to rolling	0.654	0.317	92.85714	0	1
Axle bearing fracture	0.472	0.306	92.85714	0.003	0
Caster wheel fracture	0	NA	89.28571	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.661	0.18	89.28571	0	0
Tire cracking	0.512	0.244	89.28571	0.006	0
Deflated tire	1	0	100	0	0
Stem bearing fracture	0.654	0.317	96.42857	0	0
Stem bearing corrosion	0.745	0.149	92.85714	0	0
Stem bolt fracture	0.883	0.104	96.42857	0	1
Bent fork	0	NA	100	NA	0
Fork fracture	0.781	0.21	96.42857	0	0
Fork corrosion	0.868	0.129	96.42857	0	0

Participant 4 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.696	0.11	78.57143	0	1
Axle bearing's obstruction to rolling	0.582	0.126	71.42857	0	1
Axle bearing fracture	0.204	0.118	50	0.051	1
Caster wheel fracture	0.302	0.213	75	0.043	1
Tire roll-off	0.686	0.154	85.71429	0	1
Tire worn out	0.578	0.147	78.57143	0.001	0
Tire cracking	0.473	0.174	71.42857	0.01	2
Deflated tire	1	0	96.42857	0	1
Stem bearing fracture	0.763	0.106	85.71429	0	0
Stem bearing corrosion	0.815	0.098	85.71429	0	1
Stem bolt fracture	0.582	0.13	71.42857	0	1
Bent fork	0.927	0.072	89.28571	0	2
Fork fracture	0.867	0.089	85.71429	0	2
Fork corrosion	0.832	0.091	85.71429	0	1

Participant 5 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.869	0.088	92.85714	0.869	0.088
Axle bearing's obstruction to rolling	0.768	0.156	92.85714	0.768	0.156
Axle bearing fracture	0.698	0.151	89.28571	0.698	0.151
Caster wheel fracture	0.837	0.158	96.42857	0.837	0.158
Tire roll-off	1	0	100	1	0
Tire worn out	0.462	0.322	92.85714	0.462	0.322
Tire cracking	0.9	0.98	96.42857	0.9	0.98
Deflated tire	0.65	0.322	96.42857	0.65	0.322
Stem bearing fracture	0.775	0.101	85.71429	0.775	0.101
Stem bearing corrosion	0.945	0.054	96.42857	0.945	0.054
Stem bolt fracture	0.878	0.084	92.85714	0.878	0.084
Bent fork	1	0	100	1	0
Fork fracture	0.869	0.088	92.85714	0.869	0.088
Fork corrosion	0.768	0.156	92.85714	0.768	0.156

Participant 6 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.754	0.109	85.71429	0	0
Axle bearing's obstruction to rolling	0.361	0.233	82.14286	0.022	0
Axle bearing fracture	0.364	0.268	89.28571	0.013	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.641	0.226	92.85714	0	0
Tire cracking	0.837	0.158	96.42857	0	0
Deflated tire	1	0	100	0	0
Stem bearing fracture	0.183	0.172	60.71429	0.157	0
Stem bearing corrosion	0.303	0.177	64.28571	0.063	0
Stem bolt fracture	0.307	0.187	71.42857	0.025	0
Bent fork	0.387	0.211	78.57143	0.018	0
Fork fracture	0.582	0.169	82.14286	0	0
Fork corrosion	0.365	0.178	71.42857	0.022	0

Participant 7 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.711	0.116	82.14286	0	0
Axle bearing's obstruction to rolling	0.453	0.139	67.85714	0	0
Axle bearing fracture	0.08	0.123	50	0.552	0
Caster wheel fracture	0.437	0.165	75	0	0
Tire roll-off	0.385	0.168	78.57143	0.001	0
Tire worn out	0.379	0.139	67.85714	0.002	1
Tire cracking	0.609	0.134	82.14286	0	0
Deflated tire	0.446	0.228	85.71429	0.001	0
Stem bearing fracture	0.625	0.151	82.14286	0	0
Stem bearing corrosion	0.679	0.126	82.14286	0	0
Stem bolt fracture	0.694	0.123	78.57143	0	1
Bent fork	0.581	0.133	75	0	1
Fork fracture	0.755	0.113	82.14286	0	1
Fork corrosion	0.831	0.091	89.28571	0	0

Participant 8 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.939	0.06	96.42857	0	0
Axle bearing's obstruction to rolling	0.879	0.081	92.85714	0	0
Axle bearing fracture	0.681	0.171	89.28571	0	0
Caster wheel fracture	0.487	0.173	75	0.002	0
Tire roll-off	0.781	0.21	96.42857	0	0
Tire worn out	0.517	0.115	71.42857	0	0
Tire cracking	0.349	0.156	67.85714	0.004	0
Deflated tire	0.785	0.204	96.42857	0	0
Stem bearing fracture	0.44	0.234	85.71429	0.003	0
Stem bearing corrosion	0.797	0.109	89.28571	0	0
Stem bolt fracture	0.771	0.125	89.28571	0	0
Bent fork	0.14	0.094	50	0.036	0
Fork fracture	0.557	0.144	75	0	0
Fork corrosion	0.838	0.087	89.28571	0	0

Participant 9 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.61	0.128	78.57143	0	0
Axle bearing's obstruction to rolling	0.259	0.159	64.28571	0.077	0
Axle bearing fracture	0.187	0.161	75	0.015	0
Caster wheel fracture	0.599	0.179	85.71429	0	0
Tire roll-off	0.785	0.204	96.42857	0	0
Tire worn out	0.661	0.18	89.28571	0	0
Tire cracking	0.856	0.098	92.85714	0	0
Deflated tire	0.785	0.204	96.42857	0	0
Stem bearing fracture	0.242	0.116	53.57143	0.029	0
Stem bearing corrosion	0.581	0.112	71.42857	0	0
Stem bolt fracture	0.153	0.099	42.85714	0.105	0
Bent fork	0.261	0.128	64.28571	0.02	0
Fork fracture	0.528	0.142	75	0	0
Fork corrosion	0.562	0.122	71.42857	0	0

Participant 10 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.833	0.108	92.85714	0	0
Axle bearing's obstruction to rolling	0.3	0.233	85.71429	0.007	0
Axle bearing fracture	0.091	0.131	82.14286	0.563	0
Caster wheel fracture	1	0	100	0	0
Tire roll-off	1	0	100	0	0
Tire worn out	0.757	0.164	92.85714	0	0
Tire cracking	0.781	0.21	96.42857	0	0
Deflated tire	1	0	100	0	1
Stem bearing fracture	0	0	89.28571	1	0
Stem bearing corrosion	0.712	0.131	89.28571	0	0
Stem bolt fracture	1	0	100	0	0
Bent fork	NA	NA	100	NA	0
Fork fracture	1	0	100	0	0
Fork corrosion	0.291	0.231	85.71429	0.029	0

Participant 11 test-retest reliability

Failure Modes	Kappa	SE	%agreement	p-value	Missing
Axle bearing corrosion	0.523	0.136	89.28571	0	2
Axle bearing's obstruction to rolling	0.207	0.154	85.71429	0.085	3
Axle bearing fracture	-0.116	0.162	75	0.345	3
Caster wheel fracture	0.232	0.166	78.57143	0.064	3
Tire roll-off	0.457	0.169	89.28571	0	3
Tire worn out	0.138	0.175	82.14286	0.279	3
Tire cracking	0.534	0.221	89.28571	0	3
Deflated tire	0.903	0.094	78.57143	0	2
Stem bearing fracture	0.735	0.157	53.57143	0	3
Stem bearing corrosion	1	0	64.28571	0	3
Stem bolt fracture	0.606	0.17	50	0	2
Bent fork	0.595	0.181	35.71429	0	3
Fork fracture	0.909	0.089	42.85714	0	3
Fork corrosion	0.922	0.076	42.85714	0	2

C.6 CASTER FAILURE CHECKLIST

ISWP
International Society of Wheelchair Professionals

This is an online form to collect data on castor failures using the ISWP castor failure checklist. It is recommended that you go through the castor failure checklist information guide that contains the failure evaluation instructions prior to using this checklist.

Wheelchair Manufacturer and Model (if known):

Country where wheelchair is being used:

Months of castor use (if known):

Upload two photos of failed caster highlighting failures.

Tire Failed?

- ◯ Yes
- ◯ No

Tire failure modes:

- ☐ Missing
- ☐ Roll-off
- ☐ Deflated
- ☐ Worn-out
- ☐ Tread lost
- ☐ Cracking

Wheel Failed?

- ◯ Yes
- ◯ No

Wheel failure modes:

- ◯ Missing
- ◯ Fracture

Fork Failed?

- ◯ Yes
- ◯ No

Fork failure modes:

- ☐ Missing
- ☐ Fracture
- ☐ Laterally Bent
- ☐ Loose
- ☐ Mild Corrosion
- ☐ Heavy Corrosion

Stem Bolt Failed?

- ○ Yes
- ○ Unable to evaluate
- ○ No

Stem bolt failure modes:

- ☐ Missing
- ☐ Fracture
- ☐ Bent
- ☐ Mild Corrosion
- ☐ Heavy Corrosion

Axle Bearing Failed?

- ○ Yes
- ○ Unable to evaluate
- ○ No

Axle bearing failure modes:

- ☐ Missing
- ☐ Sticky
- ☐ Fracture
- ☐ Mild Corrosion
- ☐ Heavy Corrosion
- ☐ Contamination

Stem Bearing Failed?

- ○ Yes
- ○ Unable to evaluate
- ○ No

Stem bearing failure modes:

- ☐ Missing
- ☐ Loose
- ☐ Locking
- ☐ Fracture
- ☐ Mild Corrosion
- ☐ Heavy Corrosion

Fastener Failure?

- ◯ Missing
- ◯ Unable to evaluate
- ◯ No Failures

List additional failures or add comments about this evaluation:

Note: The failure modes are only visible once the part is checked for failure.

C.7 SPANISH CASTER FAILURE CHECKLIST

Este es un formulario en línea para recolectar datos sobre fallos en las ruedas delanteras mediante el uso de la lista de verificación de fallos de ISWP. Se recomienda que se siga la guía de información de verificación de fallos ISWP que contiene las instrucciones de evaluación de fallos antes de usar esta lista de verificación.

Fabricante y Modelo de la Silla de Ruedas (si se conoce):

País en el que la silla de ruedas está siendo utilizada:

Meses de uso de las ruedas orientables delanteras (si se conoce):

Puede cargar dos fotos de la rueda delantera recalcando las fallas. En caso de no conocer el fabricante y el modelo, se recomienda que cargue las fotos.

Fallo de neumático?

- ○ Si
- ○ No

Tipos de fallos de neumático

- ☐ Faltante
- ☐ Desplazamiento
- ☐ Desinflado
- ☐ Desgaste
- ☐ Huella de neumático lisa
- ☐ Agrietamiento

Fallo de rueda?

- ○ Si
- ○ No

Tipos de fallos de rueda

- ○ Faltante
- ○ Rotura

Fallo de Horquilla?

- ○ Si
- ○ No

Tipos de fallos de Horquilla

- ☐ Faltante
- ☐ Rotura
- ☐ Doblado lateral
- ☐ Flojo
- ☐ Corrosión leve
- ☐ Corrosión severa

Fallo del vástago del perno?

- ○ Si
- ○ No es posible evaluar
- ○ No

Tipos de fallos del vástago del perno

- ☐ Faltante
- ☐ Rotura
- ☐ Doblado
- ☐ Corrosión leve
- ☐ Corrosión severa

Fallo del eje del cojinete?

- ○ Si
- ○ No es posible evaluar
- ○ No

Tipos de fallos del eje del cojinete

- ☐ Faltante
- ☐ Pegajoso
- ☐ Rotura
- ☐ Corrosión leve
- ☐ Corrosión severa
- ☐ Contaminación

Fallo del cojinete?

- ○ Si
- ○ No es posible evaluar
- ○ No

Tipos de fallos del cojinete

- ☐ Faltante
- ☐ Rotura

☐ Flojo
☐ Bloqueado
☐ Corrosión leve
☐ Corrosión severa

Fallos de Pasador

○ Faltante
○ No es posible evaluar
○ Sin fallos

Liste fallos adicionales o incluya comentarios acerca de esta evaluación:

APPENDIX D

FREQUENCY ANALYSIS OF VIBRATIONS SEEN ON CASTER TEST

FFTs for vibrations seen on a suspended caster arm without a caster and frame of the testing equipment are as below. These were recorded with only the turntable rotating. Later, FFTs seen with the Whirlwind caster at 1m/s with half inch slat impacts are shown.

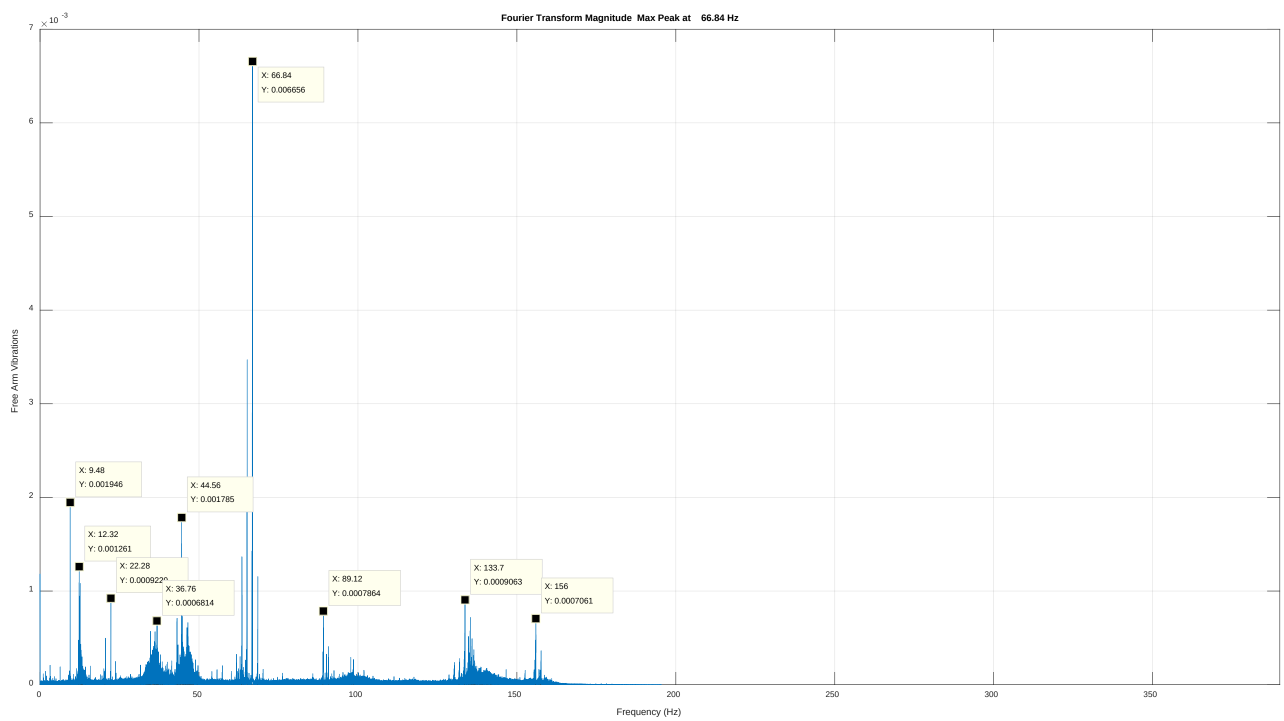


Figure D 1. FFT for vibrations seen on caster arm in forward direction

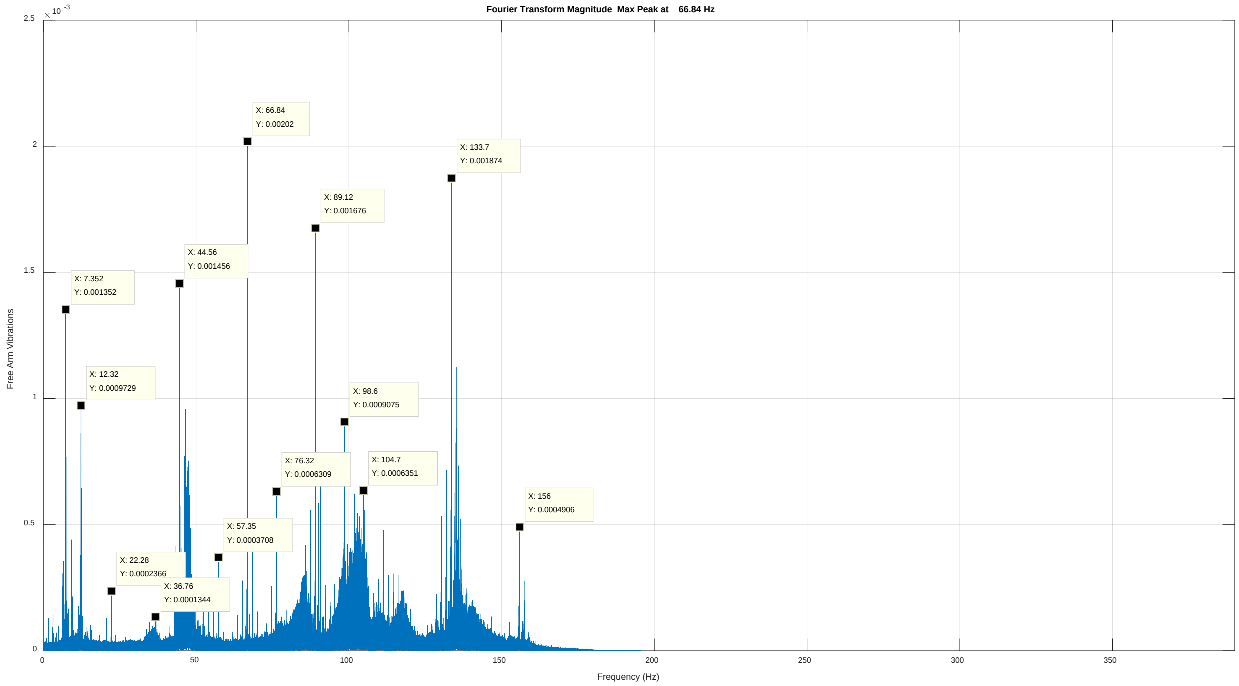


Figure D 2. FFT for vibrations seen on caster arm in lateral direction

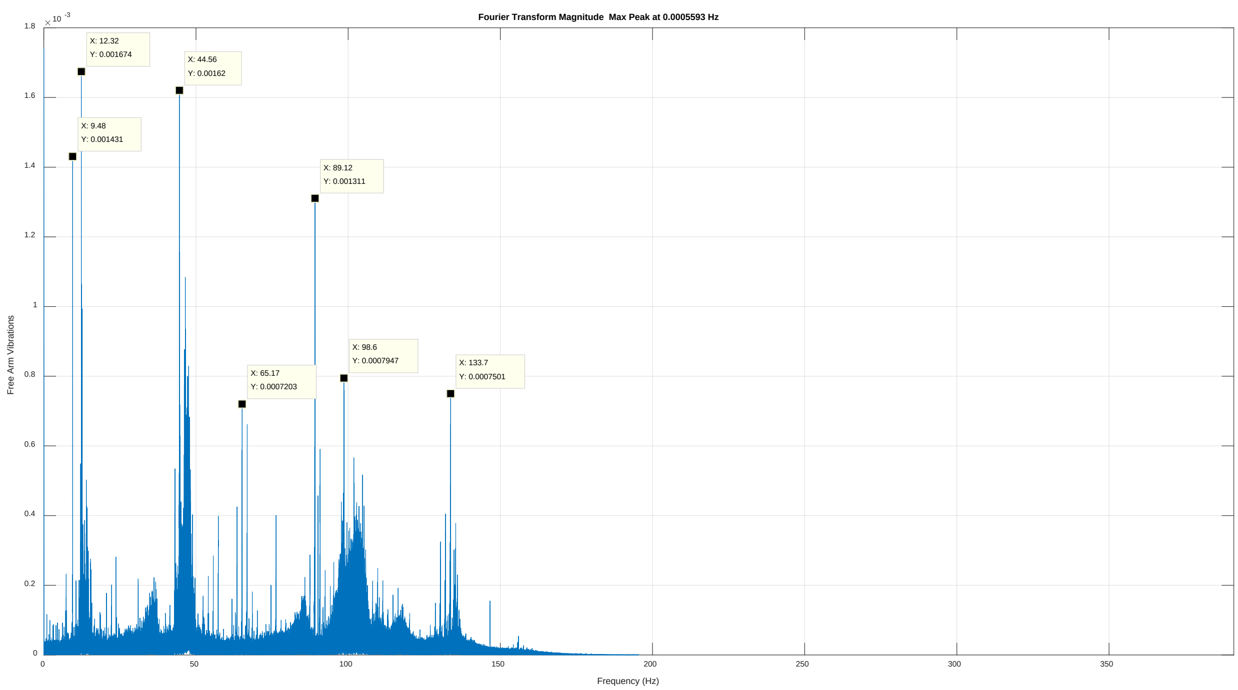


Figure D 3. FFT for vibrations seen on caster arm in vertical direction

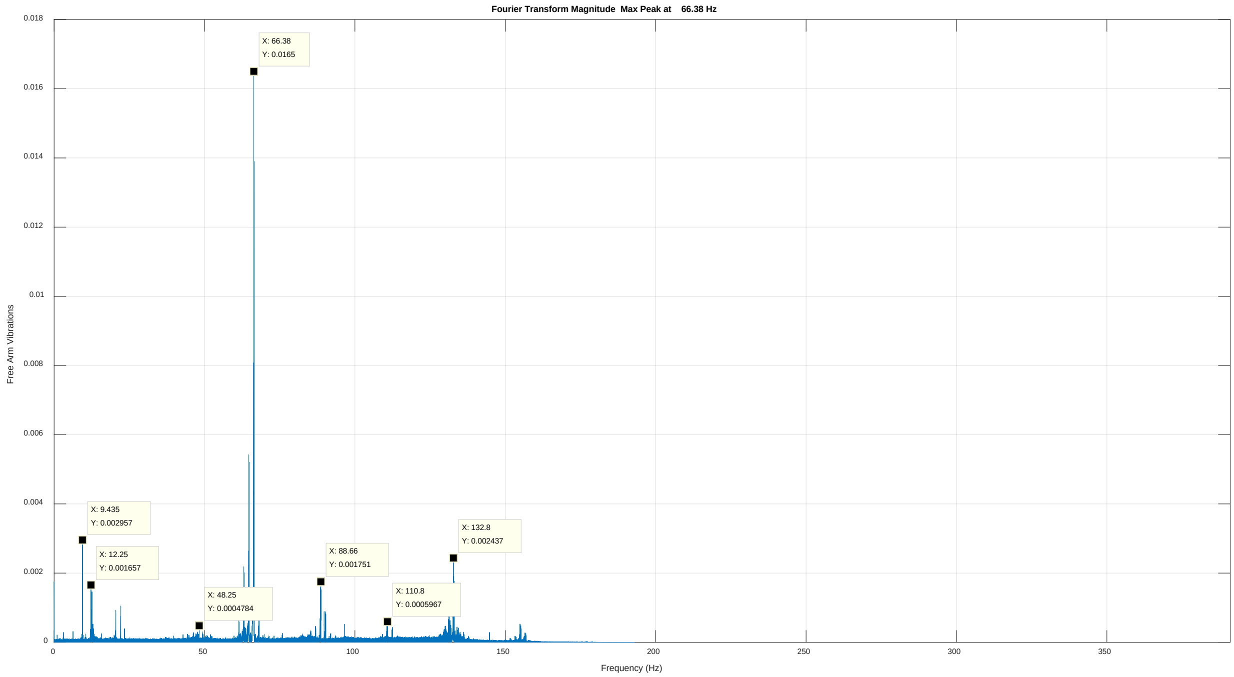


Figure D 4. FFT for vibrations seen on caster test frame in forward direction

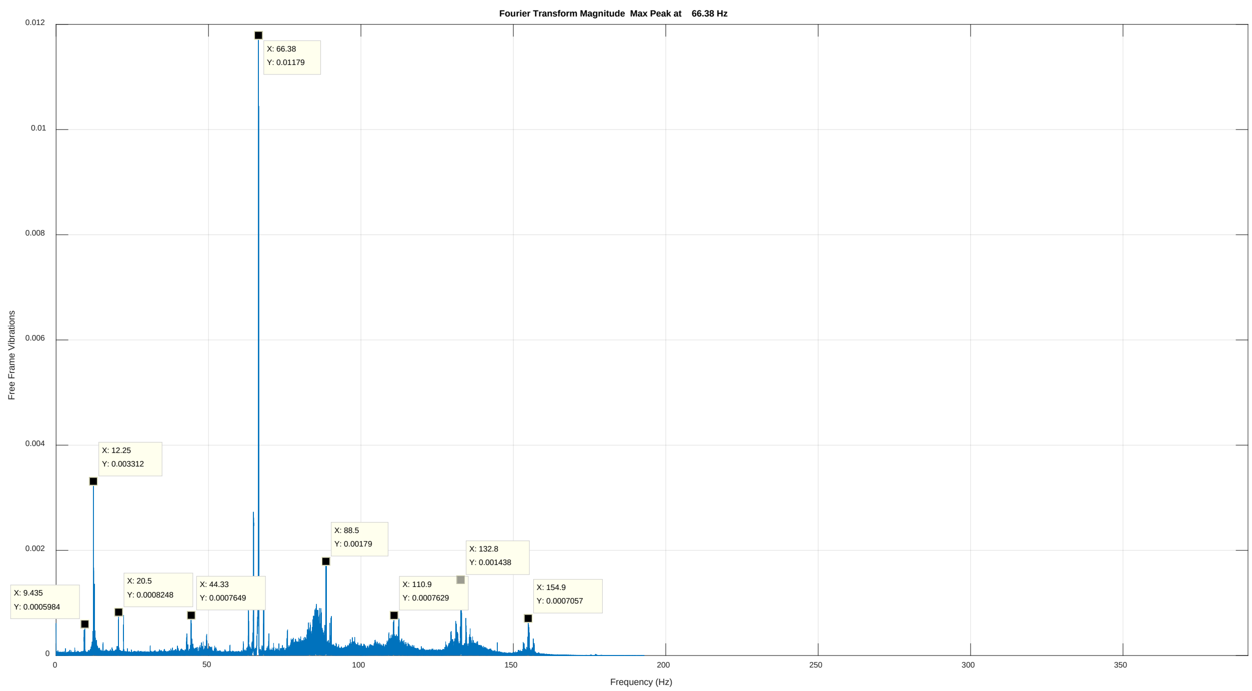


Figure D 5. FFT for vibrations seen on caster test frame in lateral direction

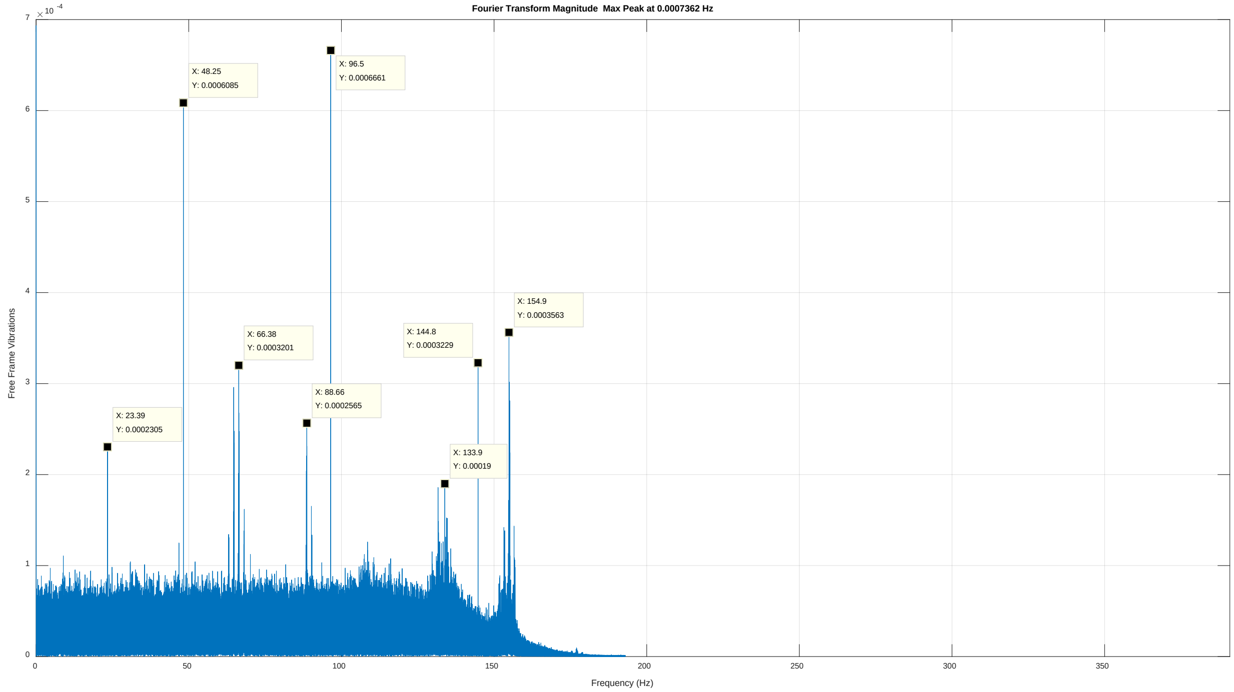


Figure D 6. FFT for vibrations seen on caster test frame in lateral direction

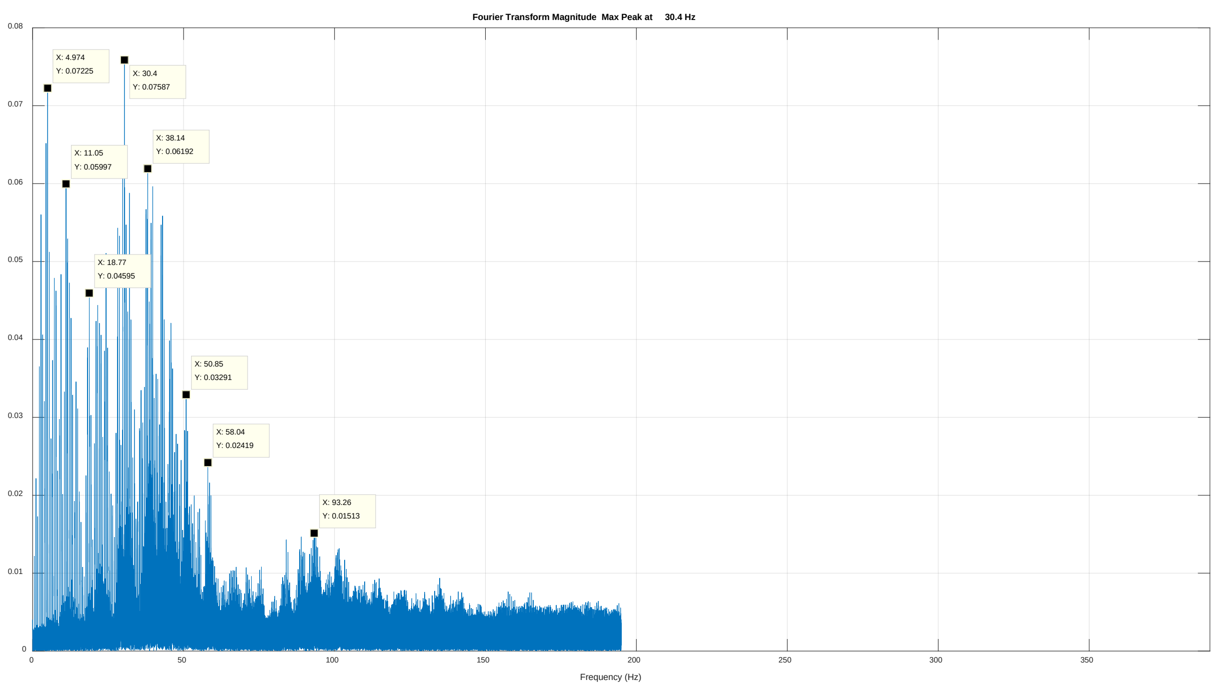


Figure D 7. FFT for vibrations seen on Whirlwind Roughrider caster fork in forward direction

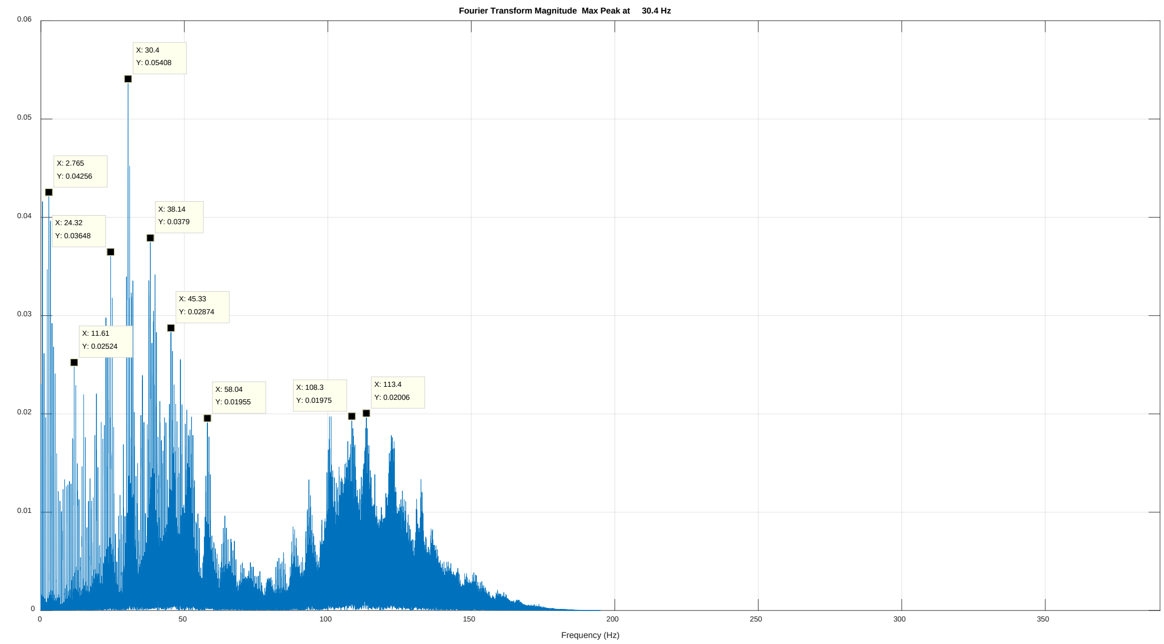


Figure D 8. FFT for vibrations seen on Whirlwind Roughrider caster fork in lateral direction

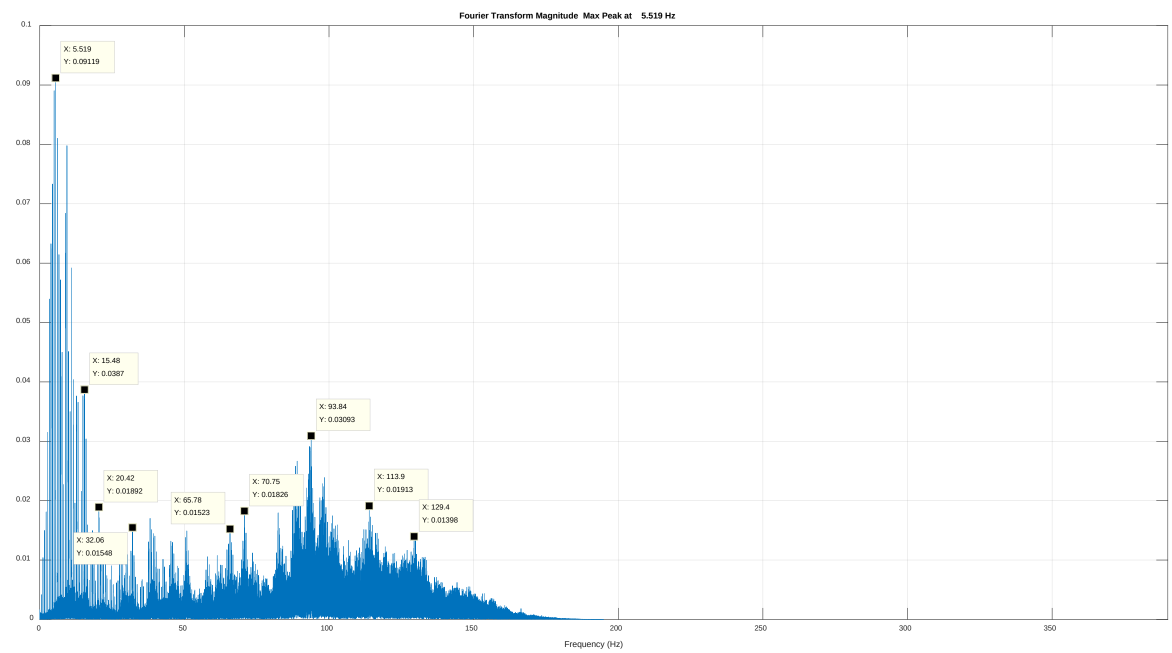


Figure D 9. FFT for vibrations seen on Whirlwind Roughrider caster fork in vertical direction

APPENDIX E

STRESS ANALYSIS

E.1 BENDING STRESS CALCULATIONS

Bending stress was calculated at the cross section where the stem bolt meets the fork as that section has minimal area and is subjected to highest stress compared to fork, wheel or axle bolt. Formulae for calculating bending moment and stress are shown below. 1g of acceleration was taken as 10.0 m/s^2 in the calculation. Weights are expressed in kg units. Unavailability of user weights is one of the limitations of this analysis. The other limitation is unavailability of wheelchair dimensions and caster position for the HKC model. Due to these limitations, it is assumed that user weight or load on the WRT caster is 20lbs (similar to what is assumed for data collection on caster test with the model). For HKC caster, 40lbs was taken as the load since it is a standard wheelchair model and based on previous experimentation during development of the caster testing equipment, standard model wheelchairs experience twice the weight seen by WRT model and other models with longer base.

Sections E.1.1 and E.1.2 show the computation of stress formulae, and Figure E 1 and Figure E 2 show the vertical accelerations and bending stresses seen by the WRR and HKC casters respectively.

E.1.1 WRR caster bending stress analysis

Bending moment = Force x length

= Mass x Acceleration (function of time in X and Z directions) x length

= $(M_{wheel} + M_{fork})$ x $A(t)_x$ x Fork Height + $(M_{user} + M_{wheel} + M_{fork})$ x $A(t)_z$ x Trail size

= (0.95) x 10.$A(t)_x$ x (0.06) + (9.07 + 0.95) x 10.$A(t)_z$ x (0.07)

= 10 (0.057 $A(t)_x$ + 0.7014 $A(t)_z$)

Bending Stress = (Bending moment x Distance of the farthest point from neutral axis)/(Moment of inertia)

= 10 ([0.057 $A(t)_x$ + 0.7014 $A(t)_z$] x 0.006)/((3.142 x 0.006^4)/4)

= 10 ([0.057 $A(t)_x$ + 0.7014 $A(t)_z$] x 0.006)/(1.018e-9)

= 6e7 [0.057 $A(t)_x$ + 0.7014 $A(t)_z$] MPa

E.1.2 HKC caster bending stress analysis

Bending moment = Force x length

= Mass x Acceleration (function of time) x length

= $(M_{wheel} + M_{fork})$ x $A(t)_x$ x Fork Height + $(M_{user} + M_{wheel} + M_{fork})$ x $A(t)_z$ x Trail size

= (0.91) x 10.$A(t)_x$ x (0.1143) + (18.14 + 0.91) x 10.$A(t)_z$ x (0.05)

= 10(0.104 $A(t)_x$ + 0.9525 $A(t)_z$)

Bending Stress = (Bending moment x Distance of the farthest point from neutral axis)/(Moment of inertia)

= 6e7 [0.104 $A(t)_x$ + 0.9525 $A(t)_z$] MPa

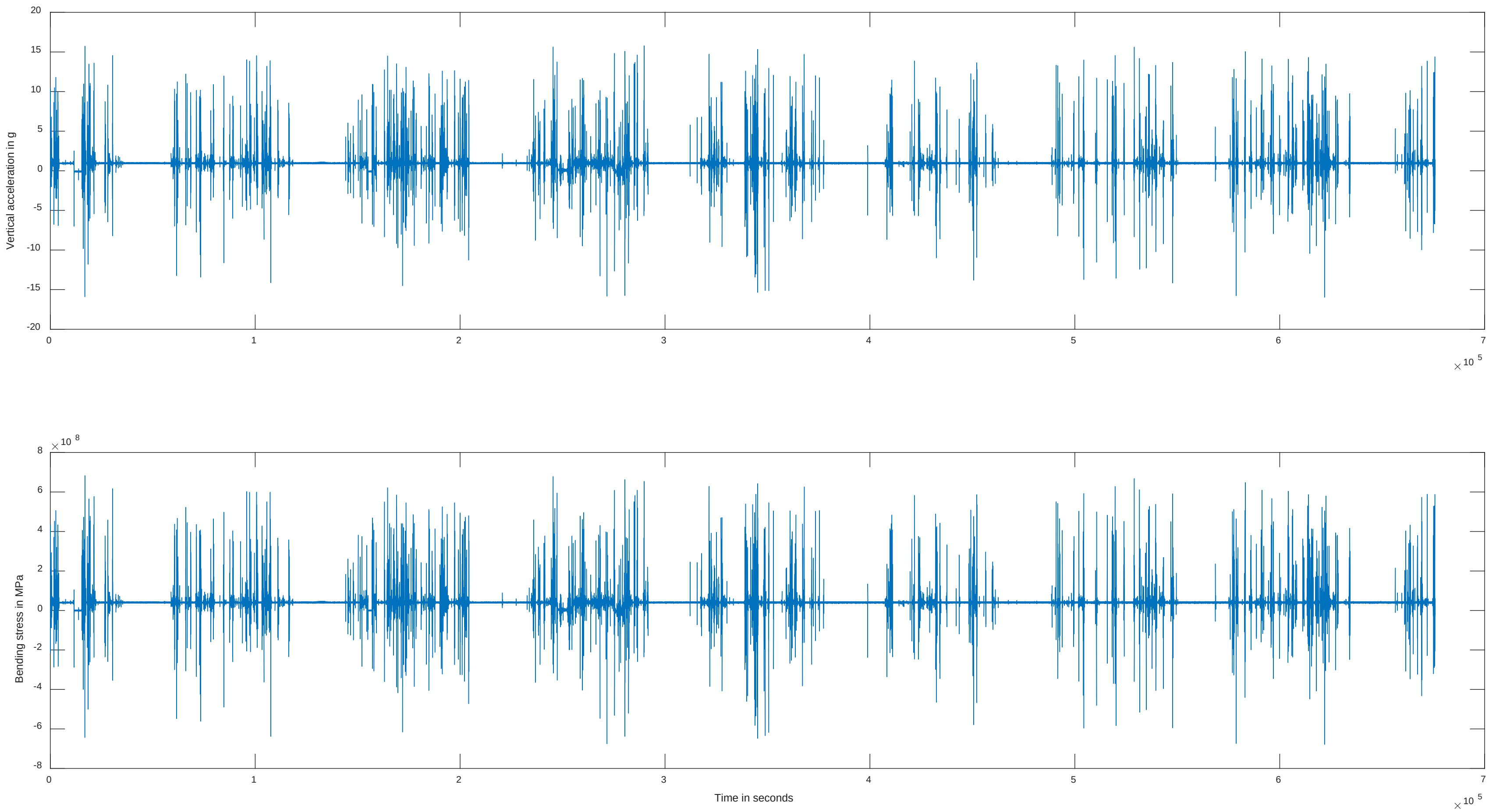


Figure E 1. Vertical accelerations and bending stresses seen by the WRR caster stem bolt.

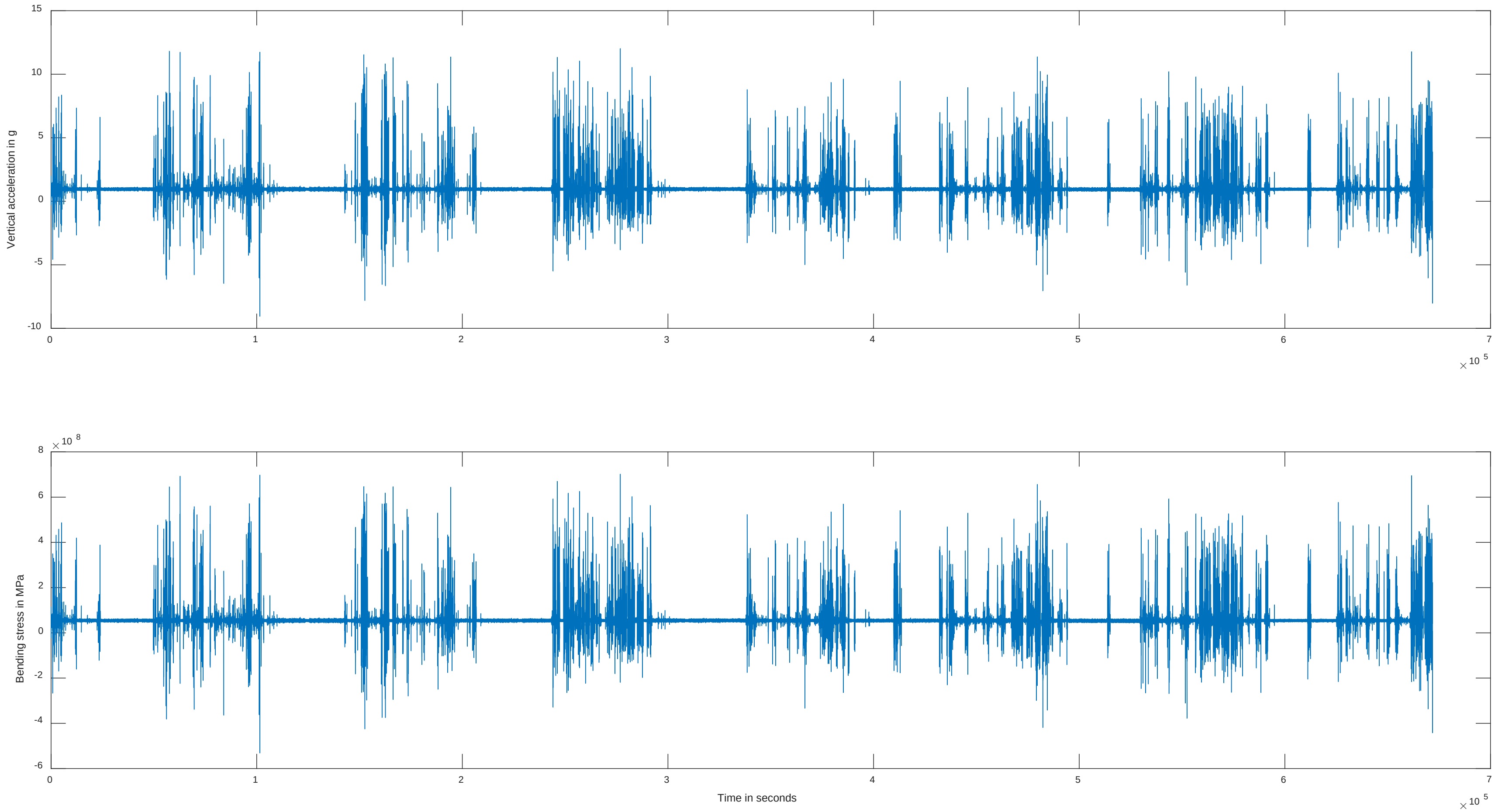


Figure E 2. Vertical accelerations and bending stresses seen by the HKC caster stem bolt.

E.2 STRESS ANALYSIS

The minimal stress that contributes to fatigue for medium strength steels was found using S-N curve shown in Figure E 3. Stress below 50% of fracture strength does not cause fatigue. Most manufacturers use the 8.8 grade bolt whose fracture strength or the ultimate tensile strength is 830 MPa[141]. Hence, stresses above 415 MPa and accelerations in the vertical direction that cause the stresses were considered for analysis.

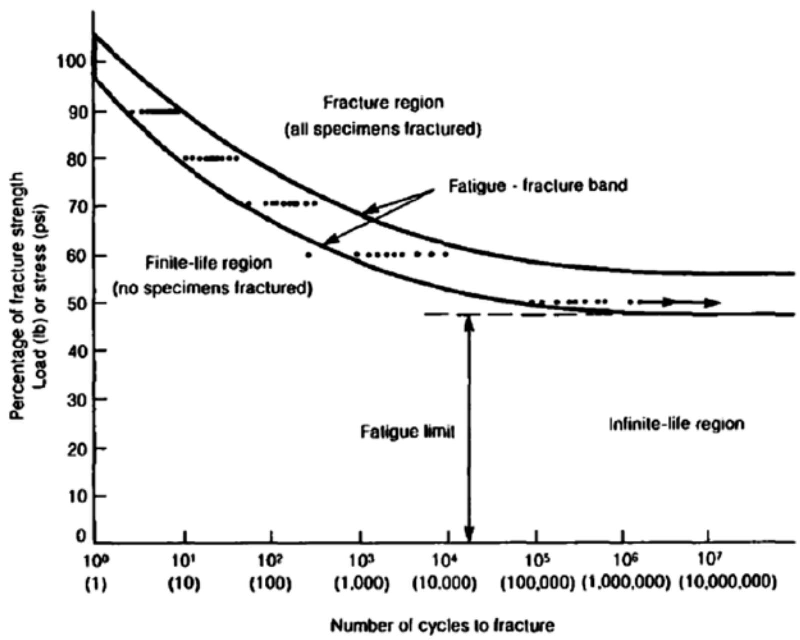
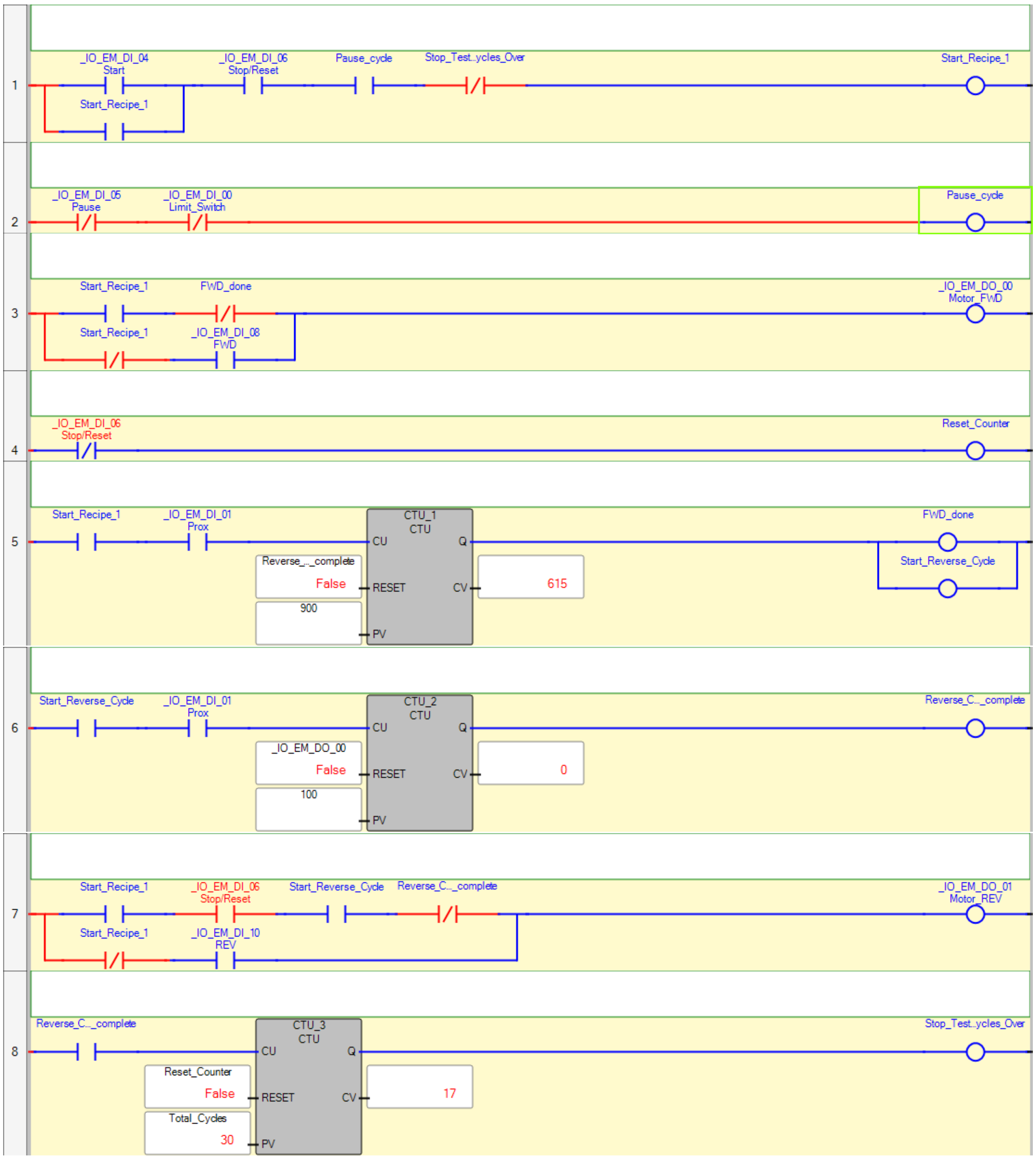
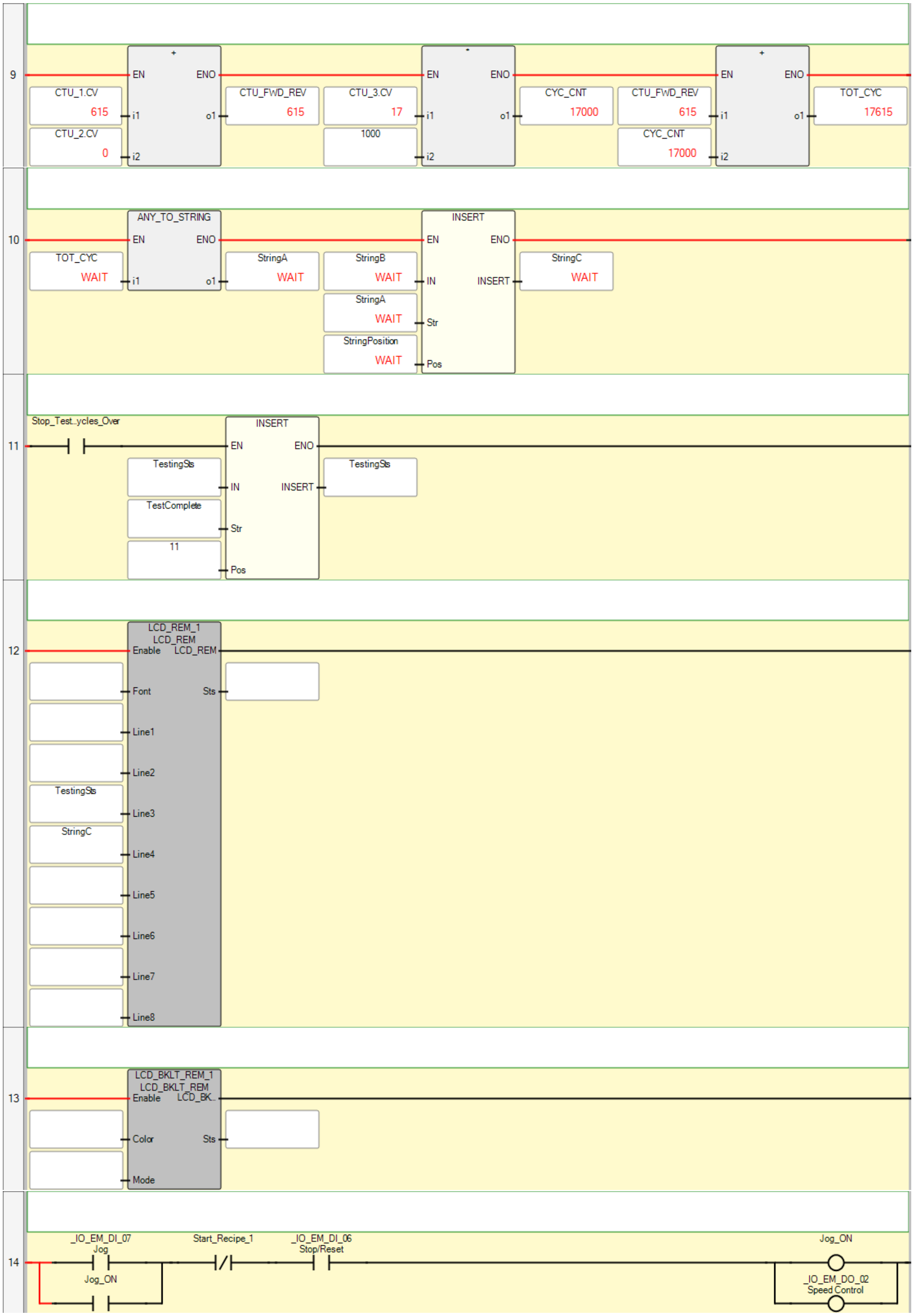


Figure E 3. Fatigue curve for typical medium strength steels[142]

E.3 MODIFIED CASTER TEST CONTROLLER PROGRAM AND VARIABLES

The background of this picture is yellow because he controller is in RUN mode compared to the OFFLINE mode shown in Section B.1. This program has 33 variables.





9
EN
ENO
CTU_1.CV
615
i1
o1
CTU_FWD_REV
615
CTU_3.CV
17
CYC_CNT
17000
CTU_FWD_REV
615
TOT_CYC
17615
CTU_2.CV
0
i2
1000
CYC_CNT
17000
10
ANY_TO_STRING
INSERT
TOT_CYC
WAIT
StringA
WAIT
StringB
WAIT
IN
INSERT
StringC
WAIT
StringA
WAIT
Str
StringPosition
WAIT
Pos
11
Stop_Test..ycles_Over
INSERT
TestingSts
TestingSts
TestComplete
11
12
LCD_REM_1
LCD_REM
Enable
LCD_REM
Font
Sts
Line1
Line2
TestingSts
Line3
StringC
Line4
Line5
Line6
Line7
Line8
13
LCD_BKLT_REM_1
LCD_BKLT_REM
Enable
LCD_BK..
Color
Sts
Mode
14
_IO_EM_DI_07
Jog
Start_Recipe_1
_IO_EM_DI_06
Stop/Reset
Jog_ON
Jog_ON
_IO_EM_DO_02
Speed Control

Variables:

Variable Start_Recipe_1
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Stop_Test_Cycles_Over
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Test_Time
(* *)
Direction: Var
Data type: TIME
Attribute: Read/Write

Variable Timer_Start
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Reset_Counter
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Jog_ON
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable CTD1_Done
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable NewVariable
(* *)

Direction: Var
Data type: STRING
Attribute: Read/Write

Variable CTU_1
(* *)
Direction: Var
Data type: CTU
Attribute: Read/Write

Variable Pause_cycle
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable FWD_done
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable Start_Reverse_Cycle
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable CTU_2
(* *)
Direction: Var
Data type: CTU
Attribute: Read/Write

Variable Reverse_Cycle_complete
(* *)
Direction: Var
Data type: BOOL
Attribute: Read/Write

Variable LCD_REM_1
(* *)
Direction: Var
Data type: LCD_REM
Attribute: Read/Write

Variable LCD_BKLT_REM_1
(* *)
Direction: Var
Data type: LCD_BKLT_REM
Attribute: Read/Write

Variable StringB
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable StringPosition
(* *)
Direction: Var
Data type: DINT
Attribute: Read/Write

Variable StringC
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable StringA
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable TestingSts
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable TestComplete
(* *)
Direction: Var
Data type: STRING
Attribute: Read/Write

Variable CTU_3
(* *)
Direction: Var
Data type: CTU

Attribute: Read/Write

Variable CTU_FWD_REV
(* *)
Direction: Var
Data type: DINT
Attribute: Read/Write

Variable CYC_CNT
(* *)
Direction: Var
Data type: DINT
Attribute: Read/Write

Variable TOT_CYC
(* *)
Direction: Var
Data type: DINT
Attribute: Read/Write

Variable Total_Cycles
(* *)
Direction: Var
Data type: DINT
Attribute: Read/Write

Variable __MO_PLUS_1
(* *)
Direction: VarTemp
Data type: BOOL
Attribute: Read/Write

Variable __MO_MULT_1
(* *)
Direction: VarTemp
Data type: BOOL
Attribute: Read/Write

Variable __MO_PLUS_2
(* *)
Direction: VarTemp
Data type: BOOL
Attribute: Read/Write

Variable __MO_ANY_TO_STRING_1
(* *)

Direction: VarTemp
Data type: BOOL
Attribute: Read/Write

Variable __MO_INSERT_1
(* *)
Direction: VarTemp
Data type: BOOL
Attribute: Read/Write

Variable __MO_INSERT_2
(* *)
Direction: VarTemp
Data type: BOOL
Attribute: Read/Write

BIBLIOGRAPHY

1. Borg, J. and Khasnabis, C., *Guidelines on the provision of manual wheelchairs in less-resourced settings*. 2008. Available from: http://www.who.int/disabilities/publications/technology/wheelchairguidelines/en/#.Va2cj8BW0ok.mendeley.

2. United Nations Department of Economic Social Affairs Population Division, *World Mortality Report*. 2015. Available from: http://www.un.org/en/development/desa/population/publications/pdf/mortality/WMR2015/WMR2015.pdf.

3. United Nations (UN), *Youth population trends and sustainable development*. 2015. Available from: http://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2015-1.pdf.

4. United Nations (UN), *Population ageing and sustainable development*. 2017. Available from: http://www.un.org/en/development/desa/population/publications/pdf/popfacts/PopFacts_2017-1.pdf.

5. United States Agency for International Development (USAID). 2016. Available from: https://www.usaid.gov/.

6. World Health Organization (WHO), *Rehabilitation 2030: A Call for Action*. 2017. Available from: http://www.who.int/disabilities/care/rehab-2030/en/.

7. World Health Organization (WHO), *Injuries*. 2017. Available from: http://www.who.int/topics/injuries/en/.

8. World Health Organization (WHO), *Road Traffic Injuries*. 2017. Available from: http://www.who.int/mediacentre/factsheets/fs358/en/.

9. Garton, F. and Urseau, I., *The Provision of Wheeled Mobility And Positioning Devices*. 2013.

10. World Health Organization (WHO), *World Report on Disability*. in *WHO Disabilities and Rehabilitation Publications*. 2011.

11. World Health Organization (WHO), *Wheelchair Service Training Package - Basic level*. 2012. Available from: http://www.who.int/disabilities/technology/wheelchairpackage/en/.

12. World Health Organization (WHO), *Wheelchair Service Training Package – Intermediate Level (WSTP-I)*. 2013. Available from: http://www.who.int/disabilities/technology/wheelchairpackage/wstpintermediate/en/.

13. Mhatre, A., Martin, D., McCambridge, M., Reese, N., Sullivan, M., Schoendorfer, D., Wunderlich, E., Rushman, C., Mahilo, D., and Pearlman, J., *Developing product quality standards for wheelchairs used in less-resourced environments.* African Journal of Disability, 2017. **6**(0) DOI: 10.4102/ajod.v6i0.288.

14. United Nations (UN), *Convention on the Rights of Persons with Disabilities*. 2006. Available from: http://www.un.org/esa/socdev/enable/rights/convtexte.htm.

15. Borg, J., Lindström, A., and Larsson, S., *Assistive technology in developing countries: a review from the perspective of the Convention on the Rights of Persons with Disabilities.* Prosthetics and orthotics international, 2011. **35**(1): p. 20-9 DOI: 10.1177/0309364610389351.

16. Marasinghe, K. M., Lapitan, J. M., and Ross, A., *Assistive technologies for ageing populations in six low-income and middle-income countries: a systematic review.* BMJ innovations, 2015.

17. Oderud, T., *Surviving spinal cord injury in low income countries: original research.* African Journal of Disability, 2014. **3**(2): p. 1-9.

18. Sheldon, S. and Jacobs, N. A., *Report of a consensus conference on wheelchairs for developing countries*. 2006. Available from: http://www.who.int/disabilities/technology/WCGconcensusconf/en/#.Va2QwYdvWAI.mendeley.

19. Visagie, S., Duffield, S., and Unger, M., *Exploring the impact of wheelchair design on user function in a rural South African setting: original research.* African Journal of Disability, 2015. **4**(1): p. 1-8.

20. Visagie, S., Scheffler, E., and Schneider, M., *Policy implementation in wheelchair service delivery in a rural South African setting: original research.* African Journal of Disability, 2013. **2**(1): p. 1-9.

21. Pearlman, J., Cooper, R. A., Zipfel, E., Cooper, R., and McCartney, M., *Towards the development of an effective technology transfer model of wheelchairs to developing countries.* Disability & Rehabilitation: Assistive Technology, 2006. **1**(1-2): p. 103-110 DOI: 10.1080/09638280500167563.

22. Constantine, D., Hingley, C. A., and Howitt, J., *Donated wheelchairs in low-income countries - issue and alternative methods for improving wheelchair provision*. 2006. p. 37-44.

23. Glumac, L. K., Pennington, S. L., Sweeney, J. K., and Leavitt, R. L., *Guatemalan caregivers' perceptions of receiving and using wheelchairs donated for their children.* Pediatric Physical Therapy, 2009. **21**(2): p. 167-175, https://insights.ovid.com/pubmed?pmid=19440126.

24. Lysack, J. T., Wyss, U. P., Packer, T. L., Mulholland, S. J., and Panchal, V., *Designing appropriate rehabilitation technology: a mobility device for women with ambulatory disabilities in India.* International Journal of Rehabilitation Research, 1999. **22**(1): p. 1-9 DOI: 10.1097/00004356-199903000-00001.

25. Sauret, C., Bascou, J., de Saint Rémy, N., Pillet, H., Vaslin, P., and Lavaste, F., *Assessment of field rolling resistance of manual wheelchairs.* Journal of Rehabilitation Research & Development (JRRD), 2012. **49**: p. 63-74.

26. Rispin, K. and Wee, J., *Comparison between performances of three types of manual wheelchairs often distributed in low-resource settings.* Disability and rehabilitation.

Assistive technology, 2015. 10.3109/17483107.2014.1002541: p. 1-7 DOI: 10.3109/17483107.2014.1002541.

27. Visagie, S., Scheffler, E., Mlambo, T., Nhunzvi, C., Van der Veen, J., and Tigere, D., *Is any wheelchair better than no wheelchair? a Zimbabwean perspective: original research.* African Journal of Disability, 2015. **4**(1): p. 1-10.

28. Hof, H., Hotchkiss, R., and Pfaelzer, P., *Building Wheelchairs, Creating Opportunities: Collaborating to Build Wheelchairs in Developing Countries.* Technology and Disability, 1993. **2**(2): p. 1-14 DOI: 10.3233/TAD-1993-2203.

29. Rispin, K., Huff, K., Parra, V., Wesley, C., and Wee, J. *An Overview of A Group of studies Done in Kenya comparing two Types of Pediatric Wheelchairs with 14 inch wide seats*. 2013.

30. United States Agency for International Development (USAID), *Wheelchair Product Table*. 2014. Available from: https://www.usaid.gov/documents/1866/resource-list-wheelchairs-less-resourced-settings#overlay-context=home.

31. Brubaker, C. E., *Wheelchair prescription: an analysis of factors that affect mobility and performance.* Journal of rehabilitation research and development, 1986. **23**(4): p. 19-26, http://www.ncbi.nlm.nih.gov/pubmed/3820118.

32. 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.* Archives of Physical Medicine and Rehabilitation, 2016. **97**(10): p. 1753-1760 DOI: 10.1016/J.APMR.2016.03.032.

33. 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.* American Journal of Physical Medicine & Rehabilitation, 2012. **91**(6): p. 463-469 DOI: 10.1097/PHM.0b013e31825ab5ec.

34. Worobey, L., Oyster, M., Pearlman, J., Gebrosky, B., and Boninger, M. L., *Differences between manufacturers in reported power wheelchair repairs and adverse consequences among people with spinal cord injury.* Archives of physical medicine and rehabilitation, 2014. **95**(4): p. 597-603 DOI: 10.1016/j.apmr.2013.11.022.

35. Calder, C. J. and Kirby, R. L., *Fatal wheelchair-related accidents in the United States.* American journal of physical medicine & rehabilitation / Association of Academic Physiatrists, 1990. **69**(4): p. 184-90, Available from: http://www.ncbi.nlm.nih.gov/pubmed/2383378.

36. Fitzgerald, S. G., Collins, D. M., Cooper, R. R. A., Tolerico, M., Kelleher, A., Hunt, P., Martin, S., Impink, B., and Cooper, R. R. A., *Issues in maintenance and repairs of wheelchairs: A pilot study.* Journal of rehabilitation research and development, 2005. **42**(6): p. 853-62, Available from: http://www.ncbi.nlm.nih.gov/pubmed/16680622.

37. Kirby, R. L. and Ackroyd-Stolarz, S. A., *Wheelchair safety--adverse reports to the United States Food and Drug Administration.* American journal of physical medicine & rehabilitation / Association of Academic Physiatrists, 1994. **74**(4): p. 308-12 DOI: 10.1097/00002060-199507000-00009.

38. Kirby, R. L. and MacLeod, D. A. *Wheelchair-Related Injuries Reported to the National Electronic Injury Surveillance System: an Update*. 2001. Reno, NV.

39. McClure, L. A., Boninger, M. L., Oyster, M. L., Williams, S., Houlihan, B., Lieberman, J. A., and Cooper, R. A., *Wheelchair repairs, breakdown, and adverse consequences for people with traumatic spinal cord injury.* Archives of physical medicine and rehabilitation, 2009. **90**(12): p. 2034-8 DOI: 10.1016/j.apmr.2009.07.020.

40. Unmat, S. and Kirby, R. L., *Nonfatal wheelchair-related accidents reported to the National Electronic Injury Surveillance System.* American journal of physical medicine & rehabilitation / Association of Academic Physiatrists, 1994. **73**(3): p. 163-7 DOI: 10.1097/00002060-199406000-00004.

41. Xiang, H., Chany, A. M., and Smith, G. A., *Wheelchair related injuries treated in US emergency departments.* Injury prevention : journal of the International Society for Child and Adolescent Injury Prevention, 2006. **12**(1): p. 8-11 DOI: 10.1136/ip.2005.010033.

42. Hotchkiss, R., *Independence through Mobility: A guide through the manufacture of the ATI-Hotchkiss Wheelchair*. 1985.

43. Jenny, K. and Susan, J. M., *Seating/wheelchair technology in the developing world: need for a closer look.* 1999, IOS Press. p. 21-27.

44. Chakwizira, J., Nhemachena, C., Dube, S., and Maponya, G., *Rural travel and disability in Leroro and Moremela villages, South Africa.* 2010.

45. Fass, M. V., Cooper, R. A., Fitzgerald, S. G., Schmeler, M., Boninger, M. L., Algood, S. D., Ammer, W. A., Rentschler, A. J., and Duncan, J., *Durability, value, and reliability of selected electric powered wheelchairs.* Archives of physical medicine and rehabilitation, 2004. **85**(5): p. 805-14, Available from: http://www.ncbi.nlm.nih.gov/pubmed/15129406

46. Gaal, R. P., Rebholtz, N., Hotchkiss, R. D., and Pfaelzer, P. F., *Wheelchair rider injuries: causes and consequences for wheelchair design and selection.* Journal of Rehabilitation Research & Development (JRRD), 1997. **34**(1): p. 58-71, Available from: http://www.ncbi.nlm.nih.gov/pubmed/9021626.

47. Toro, M. L., Garcia, Y., Ojeda, A. M., Dausey, D. J., and Pearlman, J., *Quantitative Exploratory Evaluation of the Frequency, Causes and Consequences of Rehabilitation Wheelchair Breakdowns delivered at a Paediatric Clinic in Mexico.* Disability, CBR & Inclusive Development, 2012. **23**(3): p. 48-64 DOI: 10.5463/dcid.v23i3.167.

48. Mulholland, S. J., Packer, T. L., Laschinger, S. J., Olney, S. J., and Panchal, V., *The mobility needs of women with physical disabilities in India: a functional perspective.* Disability & Rehabilitation, 1998. **20**(5): p. 168-78 DOI: 10.3109/09638289809166078.

49. Pearlman, J., Cooper, R. A., Krizack, M., Lindsley, A., Wu, Y., Reisinger, K. D., Armstrong, W., Casanova, H., Chhabra, H. S., and Noon, J., *Lower-limb prostheses and wheelchairs in low-income countries.* IEEE engineering in medicine and biology magazine : the quarterly magazine of the Engineering in Medicine & Biology Society, 2008. **27**(2): p. 12-22 DOI: 10.1109/EMB.2007.907372.

50. Toro, M., *Development, implementation, and dissemintaion of a wheelchair maintenance training program*. 2016, University of Pittsburgh.

51. Chen, W.-Y., Jang, Y., Wang, J.-D., Huang, W.-N., Chang, C.-C., Mao, H.-F., and Wang, Y.-H., *Wheelchair-related accidents: relationship with wheelchair-using behavior in active community wheelchair users.* Archives of physical medicine and rehabilitation, 2011. **92**(6): p. 892-8 DOI: 10.1016/j.apmr.2011.01.008.

52. Hansen, R., Tresse, S., and Gunnarsson, R. K., *Fewer accidents and better maintenance with active wheelchair check-ups: a randomized controlled clinical trial.* Clinical rehabilitation, 2004. **18**(6): p. 631-9, Available from: http://www.ncbi.nlm.nih.gov/pubmed/15473115

53. Armstrong, W., Reisinger, K. D., and Smith, W. K., *Evaluation of CIR-whirlwind wheelchair and service provision in Afghanistan.* Disability and rehabilitation, 2007. **29**(11-12): p. 935-48 DOI: 10.1080/09638280701240615.

54. Phillips, B. and Zhao, H., *Predictors of assistive technology abandonment.* Assistive Technology, 1993. **5**(1): p. 36-45, Available from: http://www.tandfonline.com/doi/abs/10.1080/10400435.1993.10132205.

55. World Health Organization (WHO), *Global Cooperation on Assistive Technology (GATE)*. 2014. Available from: http://www.who.int/phi/implementation/assistive_technology/phi_gate/en/.

56. World Health Organization (WHO), *Priority Assistive Products List (APL)*. 2016. Available from: http://www.who.int/phi/implementation/assistive_technology/low_res_english.pdf?ua=1.

57. International Society of Wheelchair Professionals. 2015. Available from: http://www.wheelchairnet.org/

58. Adobe Connect. 2016. Available from: http://www.adobe.com/products/adobeconnect.html#.

59. Cooper, R. A., *Wheelchair Selection and Configuration*. https://books.google.com/books/about/Wheelchair_Selection_and_Configuration.html?id=CvGK-3MK66wC&pgis=11998, New York: Demos Medical Publishing. 410-410.

60. International Organization for Standardization (ISO), *ISO - ISO Standards - ISO/TC 173/SC 1 - Wheelchairs*. 2014. Available from: http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_tc_browse.htm?commid=53792.

61. Staros, A., *Testing of manually-propelled wheelchairs. The need for international standards.* Prosthetics and orthotics international, 1981. **5**(2): p. 75-84, Available from: http://www.ncbi.nlm.nih.gov/pubmed/7301525.

62. Phillips, L. R., Axelson, P. W. W., Hobson, D. A., and McFarland, S. R. *DEVELOPMENT OF WHEELCHAIR STANDARDS*. 1983. San Diego: Rehabilitation Engineering Soc of North America.

63. McLaurin, C. A. and Axelson, P., *Wheelchair standards: an overview.* Journal of rehabilitation research and development. Clinical supplement / Veterans Administration, 1990, p. 100-103.

64. Bardsley, G., *European standards for wheelchairs.* IEEE Engineering in Medicine and Biology Magazine, 1998. **17**(3): p. 42-44 DOI: 10.1109/51.677167.

65. Cooper, R., Gonzalez, J., Rick, B., Robertson, R., and Boninger, M., *New developments in wheelchair standards*. 1996. IEEE.

66. Brubaker, C. E., *Advances in wheelchair technology.* IEEE engineering in medicine and biology magazine : the quarterly magazine of the Engineering in Medicine & Biology Society, 1988. **7**(3): p. 21-4 DOI: 10.1109/MEMB.1988.999790.

67. Hobson, D. A. *Development and Application of Wheelchair Standards: Everything most people want to know in 30 minutes or less!* 1999. Pittsburgh, PA.

68. American National Standards Institute / Rehabilitation Engineering Society of North, A. and Rehabilitation Engineering Society of North, A., *American National Standard for Wheelchairs – Volume 1: Requirements and Test Methods for Wheelchairs (including Scooters)*. 2009: New York.

69. Cooper, R. A., Boninger, M. L., and Rentschler, A., *Evaluation of selected ultralight manual wheelchairs using ANSI/RESNA standards.* Archives of physical medicine and rehabilitation, 1999. **80**(4): p. 462-7, http://www.ncbi.nlm.nih.gov/pubmed/10206612.

70. Cooper, R. A., Gonzalez, J., Lawrence, B., Renschler, A., Boninger, M. L., and VanSickle, D. P., *Performance of selected lightweight wheelchairs on ANSI/RESNA tests. American National Standards Institute-Rehabilitation Engineering and Assistive Technology Society of North America.* Archives of physical medicine and rehabilitation, 1997. **78**(10): p. 1138-44, http://www.ncbi.nlm.nih.gov/pubmed/9339166.

71. Cooper, R. A., Robertson, R. N., Lawrence, B., Heil, T., Albright, S. J., VanSickle, D. P., and Gonzalez, J., *Life-cycle analysis of depot versus rehabilitation manual wheelchairs.* Journal of rehabilitation research and development, 1996. **33**(1): p. 45-55, http://www.ncbi.nlm.nih.gov/pubmed/8868417.

72. Cooper, R. A., Stewart, K. J., VanSickle, D. P., Albright, S., Robertson, R. N., Flannery, M., and Ensminger, G. *Manual Wheelchair ISO-ANSI/RESNA Fatigue Testing Experience*. 1994. Nashville, TN.

73. Fitzgerald, S. G., Cooper, R. A., Boninger, M. L., and Rentschler, A. J., *Comparison of fatigue life for 3 types of manual wheelchairs.* Archives of physical medicine and rehabilitation, 2001. **82**(10): p. 1484-8 DOI: 10.1053/apmr.2001.26139.

74. Gebrosky, B., Pearlman, J., Cooper, R. R. A., Cooper, R. R. A., and Kelleher, A., *Evaluation of lightweight wheelchairs using ANSI/RESNA testing standards.* Journal of rehabilitation research and development, 2013. **50**(10): p. 1373-89 DOI: 10.1682/JRRD.2012.08.0155.

75. Liu, H.-y., Cooper, R. R. A., Pearlman, J., Cooper, R. R. A., and Connor, S., *Evaluation of titanium ultralight manual wheelchairs using ANSI/ RESNA standards.* Journal of rehabilitation research and development, 2008. **45**(9): p. 1251-67, http://www.ncbi.nlm.nih.gov/pubmed/19319751.

76. Liu, H.-y., Pearlman, J., Cooper, R. R. A., Hong, E.-k., Wang, H., Salatin, B., and Cooper, R. R. A., *Evaluation of aluminum ultralight rigid wheelchairs versus other ultralight wheelchairs using ANSI/RESNA standards.* Journal of rehabilitation research and development, 2010. **47**(5): p. 441-55, http://www.ncbi.nlm.nih.gov/pubmed/20803388.

77. Rentschler, A. J., Cooper, R. A., Boninger, M. L., and Fitzgerald, S. G. *Using Stability and Fatigue Strength Testing When Choosing a Manual Wheelchair*. 2001. Reno, NV.

78. Wang, H., Liu, H.-Y., Pearlman, J., Cooper, R. R. A., Jefferds, A., Connor, S., and Cooper, R. R. A., *Relationship between wheelchair durability and wheelchair type and years of test.* Disability and rehabilitation. Assistive technology, 2010. **5**(5): p. 318-22 DOI: 10.3109/17483100903391137.

79. Zipfel, E., Cooper, R. A., Pearlman, J., Cooper, R., and McCartney, M., *New design and development of a manual wheelchair for India.* Disability and rehabilitation, 2007. **29**(11-12): p. 949-62 DOI: 10.1080/09638280701240672.

80. Toro, M. L., *Comparison of a manual wheelchair designed and produced in Mexico to a wheelchair produced in China based on ISO testing and clinician and user feedback.* 2013.

81. Spinlife, *Wheelchairs*. 2016.Available from: https://www.spinlife.com/

82. Reese, N. and Rispin, K. *Assessing Wheelchair Breakdowns In Kenya To Inform Wheelchair Test Standards For Low-Resource Settings*. 2015.

83. Rispin, K. L., Geyman, T., Nemati, S., and Wee, J. *A long term paired outcomes study of Regency and APDK pediatric wheelchairs designed for less-resourced settings*. 2012.

84. Toro, M. L., Eke, C., and Pearlman, J., *The impact of the World Health Organization 8-steps in wheelchair service provision in wheelchair users in a less resourced setting: a cohort study in Indonesia.* BMC Health Services Research, 2016. **16**(1): p. 26-26 DOI: 10.1186/s12913-016-1268-y.

85. Visagie, S., Scheffler, E., Mlambo, T., Nhunzvi, C., Van der Veen, J., and Tigere, D., *Impact of structured wheelchair services on satisfaction and function of wheelchair users in Zimbabwe: original research.* African Journal of Disability, 2016. **5**(1): p. 1-11.

86. Shore, S. and Juillerat, S., *The impact of a low cost wheelchair on the quality of life of the disabled in the developing world.* Medical Science Monitor : International Medical Journal of Experimental and Clinical Research, 2012. **18**(9): p. CR533-CR542 DOI: 10.12659/MSM.883348.

87. Shore, S., *Use of an economical wheelchair in India and Peru: impact on health and function.* Med Sci Monit, 2008. **14**(12): p. Ph71-9.

88. Mukherjee, G. and Samanta, A., *Wheelchair charity: a useless benevolence in community-based rehabilitation.* Disability and rehabilitation, 2005. **27**(10): p. 591-6 DOI: 10.1080/09638280400018387.

89. Saha, R., Dey, A. K., Hatoj, M., and Podder, S., *Study of wheelchair operations in rural areas covered under the District Rehabilitation Centre (DRC) scheme.* Indian Journal of Disability and Rehabilitation, 1990, (Jul-Dec): p. 57-87.

90. Rispin, K. and Wee, J., *A paired outcomes study comparing two pediatric wheelchairs for low-resource settings: the regency pediatric wheelchair and a similarly sized wheelchair made in Kenya.* Assistive technology : the official journal of RESNA, 2014. **26**(2): p. 88-95, http://www.ncbi.nlm.nih.gov/pubmed/25112053.

91. Paralyzed Veterans of America, *The Basics Of Manual Wheelchair Maintenance*. 2013.

92. ASTM International, *ASTM B117*. 2016. Available from: https://www.astm.org/Standards/B117.htm

93. Monk, J. and Wee, J., *Factors shaping attitudes towards physical disability and availability of rehabilitative support systems for disabled persons in rural Kenya.* Asia Pacific Disability and Rehabilitation Journal, 2008. **19**: p. 93-113.

94. Kwarciak, A. M., Cooper, R. R. A., Ammer, W. A., Fitzgerald, S. G., Boninger, M. L., and Cooper, R. R. A., *Fatigue testing of selected suspension manual wheelchairs using ANSI/RESNA standards.* Archives of physical medicine and rehabilitation, 2005. **86**(1): p. 123-9.

95. 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.* Disability and rehabilitation. Assistive technology, 2018. **13**(2): p. 146-156 DOI: 10.1080/17483107.2017.1299805.

96. Human Engineering Research Laboratories. 2018. Available from: http://www.herl.pitt.edu/.

97. Institute of Caster Wheel & Manufacturers (ICWM), *ANSI ICWM: 2012 The ICWM Performance Standard for Casters and Wheels*. 2012. Available from: http://www.mhi.org/icwm.

98. International Organization for Standardization (ISO), *Castors and wheels -- Requirements for applications up to 1,1 m/s (4 km/h)*. 2004. Available from: https://www.iso.org/obp/ui/#iso:std:iso:22883:ed-1:v1:en.

99. International Organization for Standardization (ISO), *Castors and wheels — Test methods and apparatus*. 2004. Available from: https://www.iso.org/obp/ui/#iso:std:iso:22878:ed-1:v1:en.

100. Dassault Systèmes, *SolidWorks 2015*. 2016. Available from: http://www.solidworks.com/

101. Automation Direct. 2016. Available from: https://www.automationdirect.com/adc/Home/Home

102. Surplus Center, *Surplus Center - AC Induction Motor*. 2016. Available from: http://www.surpluscenter.com/Power-Transmission/Gear-Reducers-Gearboxes/Right-Angle-Shaft-Input-Gear-Reducers/40-1-RA-GEAR-REDUCER-3-35-HP-RIGHT-OUTPUT-13-325-40-R.axd.

103. Surplus Center, *Surplus Center - Motor Driver*. 2016. Available from: http://www.surpluscenter.com/Electric-Motors/3-Phase-Motors/Variable-Frequency-Drives/2-HP-TECO-VFD-230-VAC-1PH-INPUT-3PH-OUTPUT-11-3425-2.axd.

104. Rockwell Automation, *Micro820 Programmable Logic Controller*. 2016. Available from: http://ab.rockwellautomation.com/Programmable-Controllers/Micro820.

105. Rockwell Automation, *Connected Components Workbench*. 2016. Available from: http://www.rockwellautomation.com/global/products-technologies/connected-components/tools/workbench.page.

106. 80/20 Inc. 2016. Avilable from: https://8020.net/

107. Caspall, J. J., Seligsohn, E., Dao, P. V., and Sprigle, S., *Changes in inertia and effect on turning effort across different wheelchair configurations.* Journal of rehabilitation research and development, 2013. **50**(10): p. 1353-62 DOI: 10.1682/JRRD.2012.12.0219.

108. Kauzlarich, J. J., Bruning, T., and Thacker, J. G., *Wheelchair caster shimmy and turning resistance.* Journal of rehabilitation research and development, 1984. **21**(2): p. 15-29, http://www.ncbi.nlm.nih.gov/pubmed/6530672.

109. Lin, J.-T., Huang, M., and Sprigle, S., *Evaluation of wheelchair resistive forces during straight and turning trajectories across different wheelchair configurations using free-wheeling coast-down test.* Journal of Rehabilitation Research & Development (JRRD), 2015. **52**(7): p. 763-763.

110. Sauret, C., Vaslin, P., Bascou, J., Pillet, H., and Lavaste, F., *Rolling resistance index of manual wheelchairs.* Computer Methods in Biomechanics and Biomedical Engineering, 2011. **14**(sup1): p. 65-66.

111. Cooper, R. A., O'Connor, T. J., Gonzalez, J. P., Boninger, M. L., and Rentschler, A., *Augmentation of the 100 kg ISO wheelchair test dummy to accommodate higher mass: a technical note.* Journal of rehabilitation research and development, 1999. **36**(1): p. 48-54, http://www.ncbi.nlm.nih.gov/pubmed/10659894.

112. Mhatre, A., Ott, J., and Pearlman, J., *Development of wheelchair caster testing equipment and preliminary testing of caster models.* African Journal of Disability, 2017. **6**: p. 358-358 DOI: 10.4102/ajod.v6i0.358.

113. Karmarkar, A., Collins, D., and Cooper, R. *Development of a Wheelchair Assessment Checklist: Preliminary Psychometric Analyses*. 2009.

114. Rispin, K., DiFrancesco, J., Raymond, L. A., Riseling, K., and Wee, J., *Preliminary inter-rater reliability of the wheelchair components questionnaire for condition.* Disability and Rehabilitation: Assistive Technology, 2017.

10.1080/17483107.2017.1346150: p. 1-6 DOI: 10.1080/17483107.2017.1346150.

115. Qualtrics Inc., *Qualtrics.com*. 2013. Available from: https://products.office.com/en-us/business/office-365-proplus-business-software.

116. Microsoft, *Microsoft Excel*. 2016.

117. Streiner, D. L. and Norman, G. R., *Health measurement scales: a practical guide to their development and use 4 edition Oxford University Press.* New York, 2008.

118. Cohen, J., *A coefficient of agreement for nominal scales.* Educational and psychological measurement, 1960. **20**(1): p. 37-46.

119. Fleiss, J. L., Levin, B., and Paik, M. C., *Statistical methods for rates and proportions*. 2013: John Wiley & Sons.

120. Landis, J. R. and Koch, G. G., *The Measurement of Observer Agreement for Categorical Data.* Biometrics, 1977. **33**(1): p. 159-174 DOI: 10.2307/2529310.

121. IBM, *IBM SPSS statistics for Windows, version 24.0*. 2014. Available from: https://www.ibm.com/analytics/data-science/predictive-analytics/spss-statistical-software.

122. VanSickle, D. P., *Realistic road loads and rider comfort for manual wheelchairs*. 1998.

123. Mathworks, *MATLAB*. 2017. Available from: https://www.mathworks.com/products/matlab.html.

124. Gulf Coast Data Concepts, L. L. C., *GCDC X16-1D Usb-Accelerometer 3-axis Data Recorder*. 2016.

125. Tolerico, M. L., Ding, D., Cooper, R. A., Spaeth, D. M., Fitzgerald, S. G., Cooper, R., Kelleher, A., and Boninger, M. L., *Assessing mobility characteristics and activity levels of manual wheelchair users.* Journal of Rehabilitation Research and Development, 2007. **44**(4): p. 561-71.

126. Ma, Y., Li, Y., and Wang, F., *The atmospheric corrosion kinetics of low carbon steel in a tropical marine environment.* Corrosion Science, 2010. **52**(5): p. 1796-1800.

127. Mohan, P. S., Natesan, M., Sundaram, M., and Balakrishnan, K., *Atmospheric corrosion at different locations in South India.* Bulletin of electrochemistry, 1996. **12**(01): p. 91-92.

128. Natesan, M., Venkatachari, G., and Palaniswamy, N., *Corrosivity and durability maps of India.* Corrosion Prevention and Control, 2005. **52**(2): p. 43-55.

129. Syed, S., *Atmospheric corrosion of hot and cold rolled carbon steel under field exposure in Saudi Arabia.* Corrosion Science, 2008. **50**(6): p. 1779-1784.

130. Dean, S. W., Delgadillo, G. H.-D., and Bushman, J. B. *Marine corrosion in tropical environments*. 2000. ASTM.

131. Castaño, J. G., Botero, C. A., Restrepo, A. H., Agudelo, E. A., Correa, E., and Echeverría, F., *Atmospheric corrosion of carbon steel in Colombia.* Corrosion Science, 2010. **52**(1): p. 216-223.

132. Morales, J., Martin-Krijer, S., Díaz, F., Hernández-Borges, J., and González, S., *Atmospheric corrosion in subtropical areas: influences of time of wetness and deficiency of the ISO 9223 norm.* Corrosion Science, 2005. **47**(8).

133. Houska, C., *Metals for Corrosion Resistance*. 2000. Available from: https://www.nickelinstitute.org/~/Media/Files/TechnicalLiterature/CapabilitiesandLimitationsofArchitecturalMetalsandMetalsforCorrosionResistanceIII_14057b_.pdf.

134. ASTM International, *ASTM D610 - 08(2012) Standard Practice for Evaluating Degree of Rusting on Painted Steel Surfaces*. 2012. Available from: https://www.astm.org/Standards/D610.htm.

135. ASTM International, *ASTM D1654 - 08(2016)e1 Standard Test Method for Evaluation of Painted or Coated Specimens Subjected to Corrosive Environments*. 2016. Available from: https://www.astm.org/Standards/D1654.htm.

136. ASTM International, *ASTM G1 - 03(2017)e1 Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens*. 2017. Available from: https://www.astm.org/Standards/G1.htm.

137. Cooper, R. A., Wolf, E., Fitzgerald, S. G., Boninger, M. L., Ulerich, R., and Ammer, W. A., *Seat and footrest shocks and vibrations in manual wheelchairs with and without suspension.* Archives of physical medicine and rehabilitation, 2003. **84**(1): p. 96-102 DOI: 10.1053/apmr.2003.50069.

138. Axelson, P., Minkel, J., Chesney, D., and Thomas, P., *A Guide to Wheelchair Selection*. http://www.wheelchairnet.org/wcn_prodserv/docs/pdf/axbook_sec1.pdf1994.

139. Cooper, R. A., Robertson, R. N., VanSickle, D. P., Stewart, K. J., and Albright, S. J., *Wheelchair impact response to ISO test pendulum and ISO standard curb.* IEEE Transactions on Rehabilitation Engineering, 1994. **2**(4): p. 240-246 DOI: 10.1109/86.340874.

140. Bertocci, G. E. E. J., Esteireiro, J., Cooper, R. A., Young, T. M., and Thomas, C., *Testing and evaluation of wheelchair caster assemblies subjected to dynamic crash loading.* Journal of rehabilitation research and development, 1999. **36**(1): p. 32-41, http://www.ncbi.nlm.nih.gov/pubmed/10659892.

141. ASTM International, *ASTM F568M*. 2007. Available from: https://compass.astm.org/Standards/WITHDRAWN/F568M.htm.

142. Boyer, H. E., *Atlas of fatigue curves*. 1985: ASM International.