Novel Test Track for Whole Wheelchair Testing

Bonnie Gonzalez, BS
Anand Mhatre, PhD
Don Schoendorfer, PhD

Introduction

In the developed world, a wheelchair's (w/c) worthiness for sale is proven by satisfying a series of standards, such as described in ISO 7176 (International Organization for Standardization, 2014). Terrain and lifestyles in developing countries are more demanding, suggesting that new standards are needed. The goals for creating our test track (LOTUS) include: capacity to expose up-to four w/c's to identical controlled forces, inclusion of w/c obstacles that mimic the forces and strains seen by w/c users in developing countries, and creating testing processes that reliably enable design optimization.

Learning Objectives

1. Recognize that different standards are required to test for the adverse environments seen in developing countries.
2. Compare and contrast LOTUS testing system with current testing standards.
3. Create controlled testing processes and procedures that simulate stress, strain, and acceleration on w/c's used in developing countries.

Methods

LOTUS Description and Features

LOTUS consists of, a 5-foot-wide by 40-foot-long conveyor belt, a programmable controller that sets the surface speed to 0-5 MPH, and obstacles bolted onto the belt to simulate different terrains. Each w/c is held stationary as the belt surface moves below and is free to move in all directions except for-aft. Each w/c is tethered to a horizontal beam on the track via the dummy's knees. This tethering method was used because the dummy's knees are located at the height of the top of the push rim, which is what an independent user would use to self-propel. This method also allows the w/c to self-center on the track after impacting an obstacle.

Figure 1. LOTUS. Much of the design and all the construction of LOTUS was done in collaboration with RPM and Associates and the South Dakota School of Mines and Technology, Rapid City, SD.

LOTUS can expose up to four w/c's at a time to the exact same testing conditions. Each w/c station is divided by a horizontal beam. The beam has 4 slots that the w/c can be tethered to. Each slot represents a different path/terrain that the w/c can travel on. This becomes useful when testing multiple w/c's. It can be used to run different tests simultaneously.

Obstacles are bolted onto the belt using elevator bolts, and new holes can be punched into the belt to accommodate a variety of obstacles. For this investigation, 12 mm high slats, identical to the ones described in ISO 7176-8 (International Organization for Standardization, 2014), are bolted onto the belt, in line with each wheel, and equally spaced apart.

An infrared curtain sensor is located behind each w/c station to detect catastrophic failures. If the light curtain is broken, the test stops automatically.

Figure 2. GEN_2 w/c tethered to LOTUS.

Test Dummy

A 100 kg steel dummy (International Organization for Standardization, 2014) was strapped to a FWM GEN_2 w/c in two places to prevent it from sliding off the w/c and from rattling during testing. A ratchet strap was hooked to the dummy's left knee and wrapped around the w/c frame to the right knee. This prevented the dummy from sliding off the w/c during testing. The second ratchet strap hooked on to the left side of the dummy's torso, wrapped around the w/c frame, and then hooked back on to the right side of the torso. This prevented the dummy from bouncing back and forth after impacting an obstacle.

A 2-inch-thick open-celled foam is placed between the dummy's bottom and the w/c cushion. A 3/4-inch closed-celled foam is placed between the dummy's back and the backrest. The foam is oversized to prevent the dummy's sharp edges from coming in direct contact with the upholstery. This would cause accelerated wear and tear on the upholstery which is not the scope of the test.

The dummy's feet are secured on the footrests with four large zip ties to prevent them from sliding off the footrests. A 1/2-inch thick rectangular piece of foam is placed between the bottom of the dummy's foot and the footrest.

Test Protocol

LOTUS was programed to run at a surface speed of 1 m/s. An activity log was kept for each w/c. The time and date were recorded any time the w/c underwent maintenance or when it experienced catastrophic failure. The test was ended when the w/c frame developed a crack. All other w/c components were replaced if broken, and testing was resumed.

Test Wheelchair

FWM GEN_2, medium sized, w/c's were used for the tests described in this paper. The GEN_2 is a non-collapsible w/c made from 25 mm OD and 22 mm ID Chinese standard Q195 steel tubing. It consists of two side frames that are connected by three crossbars near the casters, the seat, and the push handles. The crossbars determine the w/c width and they come in four sizes, S, M, L, and XL. The rear wheels are 26" pneumatic tires with medium tread. The front casters are 7.87" hard rubber. The tires are inflated to 35 psi at the beginning of each test.

LOTUS Validation in the Field

To validate testing conditions on LOTUS, a GEN_2 w/c was instrumented with accelerometers and strain gages as described below. The measured data was compared between LOTUS, double-drum, and the field. Data was collected from 5 participants in rural Kenya, and 4 participants in Mexico during typical daily use. Approval for the study was obtained through the organization's internal review process. Subject participation was voluntary. Participants could withdraw at any time or choose not to complete any task.

The GEN_2 was instrumented with two +/- 50 g, triaxial piezoelectric accelerometers from Dytran Instruments, located on the left and right casters as shown in Figure 3. The accelerometers were oriented to measure G-force acting on the w/c frame in the vertical, lateral, and for-aft direction. Four 120 ohm, LY11 linear strain gages from OMEGA were fixed on the right and left side of the frame, approximately four inches away from the weld that connects the caster barrel to the main frame. The linear gages were placed 90˚ away from each other around the steel tube. Previous tests have shown the area near the weld to be prone to cracking. Similar methods have been used previously to compare different cross-brace designs for folding manual w/c's (Cooper et al.,1999).

Data was collected using HBM's QuantumX 1601B Measuring Amplifier for acceleration, and QuantumX 1615B Strain Gage Amplifier for strain. Acceleration data was sampled at 9600 Hz and strain data was sampled at 2400 Hz to prevent aliasing. By measuring strain and acceleration we hoped to capture the strain magnitude and direction that the tubular frame experiences during testing. This data could help determine the forces that cause the frame to fail.

The acceleration data for the double drum was provided by the University of Pittsburgh and was measured using the X200-4, 3-axis, +/- 200 g accelerometer and data logger, manufactured by Gulf Coast Data Concepts. The acceleration data collected on the double drum was sampled at 400 Hz.

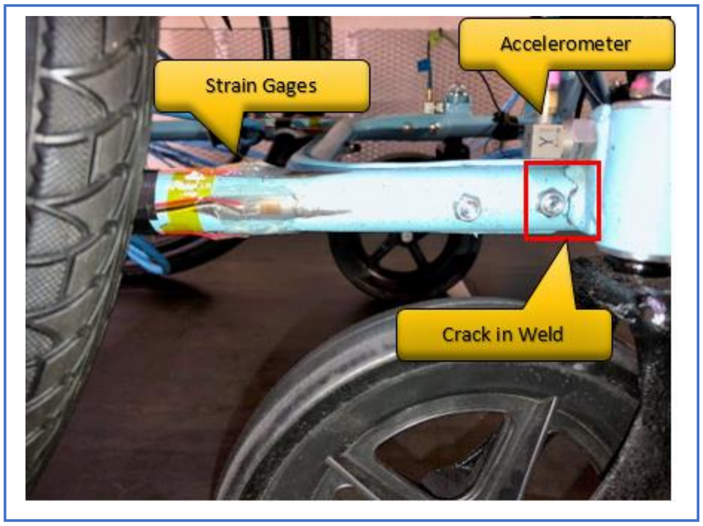

Figure 3. Instrumented GEN_2.

The participants from Kenya were all teenagers, 3 males and 2 females. All participants fit into a GEN_2 Medium sized w/c. All participants self-propelled and did not require additional help to get around. The data was collected around their school campus. The walkway surfaces were uneven and consisted of a combination of dirt, grass, and concrete.

The participants from Mexico were all adults, three males and one female. The participants ranged in size from M to XL. The w/c was constructed to fit each user by switching out the crossbars, but the same side frames were used for all participants. The participants also ranged on level of independency. Two of the participants were completely independent and self-propelled on their own, and the others required some assistance. The data was collected during typical daily use. The road surfaces were uneven and consisted of a combination of dirt, rocks, and concrete. Enough acceleration and strain data were collected to approximate one day's worth of travel for each participant. Distances ranged from 0.2 miles to 2.0 miles.

A portable 4' x 8' plank was designed to simulate a test on LOTUS, in the field. Three pairs of 12 mm high slats were bolted onto the plank, in line with each wheel, and equally spaced apart. Acceleration and strain were measured as an attendant pushed the subjects in their w/c over the plank at walking speed. Only the subjects in Mexico participated in this part of study. This data was compared with the data collected from the 100 kg dummy on LOTUS.

Fatigue life was estimated for each participant using Miner's linear cumulative damage rule (Hiatt, 2016). The test duration was approximately equal to one days' worth of travel for the participants, so fatigue life was calculated in days-to-failure. Fatigue life for LOTUS was calculated based on the assumption that a user travels 800 m a day (Mhatre, Ott, & Pearlman, 2017).

The S-N curve for Q195 steel was estimated and interpolated to extract life cycles at any given stress amplitude (Shigley & Mischke, 2001). A conservative minimal amplitude of 25% of the estimated endurance limit for Q195 steel was used for fatigue analysis. The "Rainflow Counting" method was used to extract fatigue cycles from the strain histories. The data was then exported to MATLAB where the fatigue life was calculated in days-to-failure and then converted to years-to-failure by dividing by 365 days. Fatigue life estimates presented here are based on number of stress cycles. They do not account for corrosion and other environmental factors. Due to the length restrictions of this paper, the fatigue analysis calculations will not be described in detail.

Results

We have identified several areas that we intend to improve on the GEN_2 to increase longevity on LOTUS. We wish to focus on just one for now. The GEN_ 2 frame fractures in the tubing adjacent to the weld that connects the caster barrel to the main frame as can be seen in Figure 3. A significant improvement in longevity was accomplished by welding a small gusset between the frame tubing and the caster barrel. This extended the life of the w/c by 8X's. See Figure 4.

Figure 4. Improved GEN_2 with welded gusset.

To summarize the large data sets collected in the Kenya and in Mexico, peak acceleration values were extracted at 5Hz intervals and the RMS of the peak values was calculated for the entire data set. The average of all the participants in Kenya and Mexico is displayed in Figure 5.

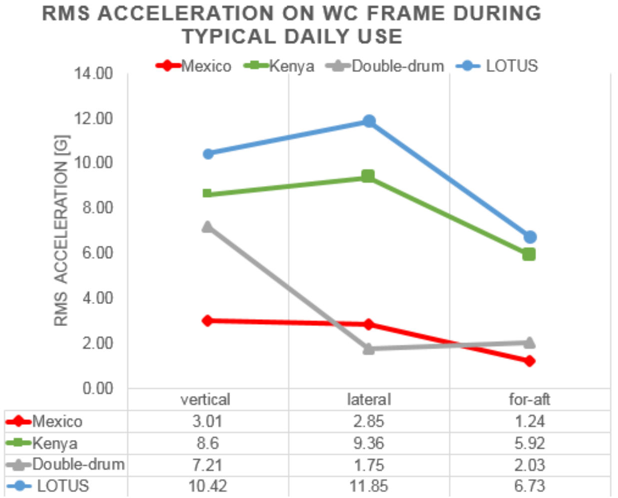

Figure 5. RMS acceleration during typical daily use.

From Figure 5 it is clear that the accelerations measured in Kenya were larger than those measured in Mexico. The w/c in Mexico, on average, experienced the least accelerations of all. Over 65% of the measured acceleration on the double drum was concentrated in the vertical direction, with the least acceleration concentration in the for-aft direction. The w/c in Kenya experienced higher accelerations than the double drum, however the w/c on LOTUS, for all three directions, experienced the largest accelerations of all the w/c's measured. The w/c on LOTUS experienced the largest acceleration in the vertical and lateral direction and the lowest acceleration in the for-aft direction. The data collected in Kenya and Mexico follow a similar pattern, but at a lower scale. The accelerations measured on LOTUS were more similar to those measured in Kenya, with accelerations that were about 20% higher.

Table 1 summarizes the fatigue life for the right and left side of the w/c frame along with the estimated distance traveled. It is important to note that time-to-failure is not directly correlated to distance traveled. Although participant 3 traveled the furthest distance of 3.2 km, the w/c experienced less fatigue damage than participant 1, who traveled only 1.6 km. The fatigue life for the w/c tested on LOTUS was significantly less than all the other w/c's. The time-to-failure for the w/c of the participant who caused the most damage was 2,104 days, while the time-to-failure for the w/c on LOTUS was 27 days. That is a 7,693% decrease. During actual testing of the GEN_2 to destruction on LOTUS, the time-to-failure was equivalent to 90 days. That is over 3X's more than the calculated fatigue life using the conservative approach.

Table 1. Fatigue Life Estimates for participants in Mexico and 100 kg dummy on LOTUS.

Fatigue Life					
		Right Frame		*Left Frame*	
Participants	Distance Traveled per day (km)	Days to failure	Years to failure	Days to failure	Years to failure
1	1.6	2,104	5.8	3,338	9.1
2	0.5	3,555	9.7	6,328	17.3
3	3.2	6,605	18.1	12,855	35.2
4	0.2	86,225	236.2	254,710	697.8
100 kg Dummy (LOTUS)	0.8	27	0.1	33	0.1

A summary of the data collected from the 4 participants in Mexico while they propelled across the plank with ridges, is shown in Figure 6. The stress amplitudes were compared with those measured with the 100 kg dummy and a 75 kg dummy on LOTUS. The results are displayed in Figure 6.

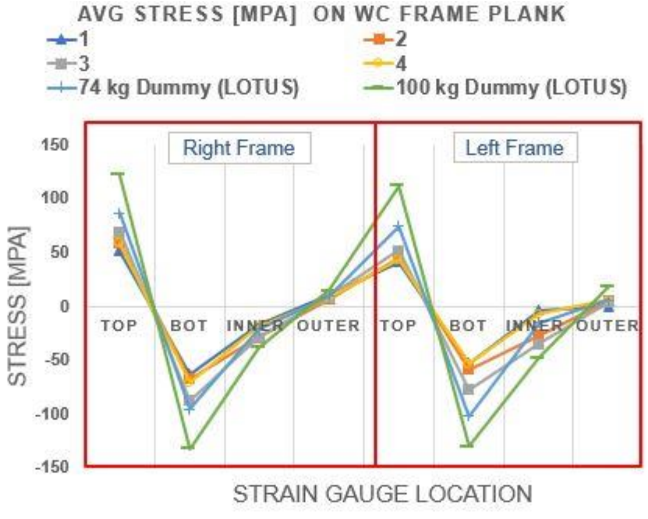

Figure 6. Stress data on plank with slats.

It can be seen from Figure 6, that the w/c experienced similar patterns of strain with all the participants. As has been the case before, the w/c experienced the highest strain with the 100 kg dummy. This suggests that the 100 kg dummy simulates harsher conditions than those found of typical w/c users in Mexico. When the weight of the dummy was decreased to 75 kg, the stresses on the frame decreased as well. This result indicates that there is a direct correlation between w/c load and stress on the frame, which subsequently determines fatigue life.

Discussion

Our acceleration data analysis suggests that the w/c users we evaluated in Kenya were more active than the w/c users in Mexico. This was confirmed in person as well. The acceleration data also suggests that LOTUS simulates the motions of the w/c's in the field more closely than the double drum, since they follow a similar pattern. Based on the acceleration data from University of Pittsburgh, the double drum test focuses on the forces in the vertical direction the most, however, the data from Kenya and from LOTUS suggests that high accelerations are experienced in the lateral and for-aft direction as well.

Our fatigue life analysis suggests that the lateral forces do not affect the life of the w/c as much as the vertical forces do. Based on this assumption, the double drum might be a suitable fatigue test for the w/c's of the users we evaluated in Mexico but would be inappropriate for the w/c users in Kenya, as it comes up short. Both the acceleration and the strain data suggest that LOTUS with the 12 mm slats simulates harsher conditions than what is found in the field but comes close to simulating w/c use in Kenya.

Conclusion

LOTUS was designed with the intention of more closely reproducing the terrain conditions found in countries FWM operates. We believe that the conveyor belt design can be adapted to simulate different terrains effectively. LOTUS' ability to expose up to four w/c's to the same exact testing conditions will allow multiple w/c's to be tested and compared side by side. This can potentially reduce testing time and increase reliability.

We realize that the testing standards described in ISO 7176-8 (International Organization for Standardization, 2014) have been around for decades and have served developed countries well, but studies have shown that w/c's that are ISO-qualified, fail prematurely in less-resourced environments (LREs) (Mhatre et al., 2017). Different testing methods must be developed to adequately test w/c's designed for LRE's. This paper is the first of many more we plan to offer as we fine tune obstacle designs, data collection & analysis, to validate and correlate our ability to simulate user conditions in the field.

Future Work

Future work will include:

- Collecting more strain and acceleration data from the field that can be used to replicate the strains and stresses with obstacles on LOTUS. This will facilitate a correlation between test time on LOTUS and estimated w/c life in the field.
- Collecting and comparing strain measurements of w/c tested on LOTUS with the double drum.
- Exposing w/c's to accelerated environmental testing combined with fatigue testing on LOTUS. Previous studies have shown that environmental factors significantly influence time-to-failure of critical wheelchair components (Mhatre, Ott, & Pearlman, 2017).
- Use data from LOTUS to optimize the relationship between cost and longevity of wheelchairs specifically designed for use in LRE's.
- And we invite organizations who are designing w/c's in developing countries to participate in our efforts by letting us test their wheelchairs.

References

1. Cooper, Rory & Digiovine, Carmen & Rentschler, Andrew & M. Lawrence, Brad & L. Boninger, Michael. (1999). Fatigue-life of two manual wheelchair cross-brace designs. Archives of physical medicine and rehabilitation. 80. 1078-81. 10.1016/S0003-9993(99)90064-3.

2. Hiatt, John, 2016, 'Calculate Damage with Miners Rule', viewed from https://community.plm.automation.siemens.com/t5/Testing-Knowledge-Base/Calculating-damage-with-Miner-s-Rule/ta-p/355057

3. International Organization for Standardization, 2014, ISO – ISO Standards – ISO/TC 173/SC 1 – Wheelchairs

4. Mhatre, A., Ott, . & Pearlman, J., 2017, 'Development of wheelchair caster testing equipment and preliminary testing of caster models', African Journal of Disability 6(0), a358. https://doi.org/10.4102/ajod.v6i0.358

5. Mhatre, A., Martin, D., McCambridge, M., Reese, N., Sullivan, M., Schoendorfer, D., Wunderlich, E., Rushman, C., Mahilo, D. & Pearlman, J., 2017, 'Developing product quality standards for wheelchairs used in less-resourced environments', African Journal of Disability 6(0), a288. https://doi.org/10.4102/ajod.v6i0.288

6. Shigley, Joseph Edward., and Charles R. Mischke. Mechanical Engineering Design. McGraw-Hill, 2001, pp. 277 – 289. Print.

Conflict of interest

Bonnie Gonzalez and Don Schoendorfer, PhD are employees of FWM. FWM funded the design and construction of LOTUS.