A Study on Vibration and Mechanical Impact of Medical Electric Wheelchairs for Vulnerable Driver

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***Abstract*— There are test items for lithium-ion batteries in reliability testing for automobiles and motorcycles, but equivalent test items have not yet been established for mobility scooters (also known as electronic wheelchairs). To evaluate the lithium-ion battery pack or system mounted on a mobility scooter, it is necessary to test vibrations and mechanical shock while driving, independent of tests for the lithium-ion battery cells. In an effort to meet this need, test profiles were established for mobility scooter lithium-ion batteries by performing on-road driving tests and mechanical shock tests.**

The proposed test profiles were validated using robust statistics and proficiency statistics. The safety of the test profiles was tested in a nationally accredited testing laboratory. As a result, the lithium-ion battery mounted on the mobility scooter was found to have incurred no leakage, short circuit, burst, or explosion. The vibration and mechanical shock test profiles proposed in this study are expected to serve as basis data for establishing standards for mobility scooter safety and reliability.

***Index Terms*—lithium-ion battery, mobility scooters, reliability test, vibration, mechanical shock, robust statistics**

I. Introduction

Compared with the general population, people with physical disabilities have significantly diminished ability to perceive the environment and are therefore at higher risk of missing warning signs of imminent fire or explosion, resulting in a lower chance to escape. This poses a serious threat when they use mobility scooters (motorized wheelchairs). With the scooter frames becoming smaller, lighter, and more convenient in recent years, various types of foldable mobility scooters have emerged. Along with this trend, conventional lead-acid batteries have been increasingly replaced by lithium-ion batteries in a wide range of products. This implies that people with physical disabilities are constantly exposed to the risk of lithium battery fires and explosions [1].

Against this background, this study was conducted to establish reliable test profiles for safety testing for lithium batteries used in mobility scooters by experimentally examining vibrations and mechanical shock while riding a mobility scooter.

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As shown in Fig. 1, random vibrations and mechanical shock are test items for lithium-ion batteries as part of reliability testing for automobiles and motorcycles. However, they have not yet been developed as test items for mobility scooters. Therefore, we try to create a standard for lithium battery testing of electric wheelchiars, using vehicle and motorcycle standards, as shown in Fig. 2 [2][3].

In an effort to bridge this gap, the acceleration, velocity, and impact force working on a lithium-ion battery mounted on a mobility scooter while driving by simulating driving conditions were calculated, and the safety test profiles were determined by performing on-road driving tests and impact tests. Then, the reliability of the test data was verified in a statistical validation process. The safety of the test profiles established in this study was tested and verified in a nationally accredited testing laboratory.

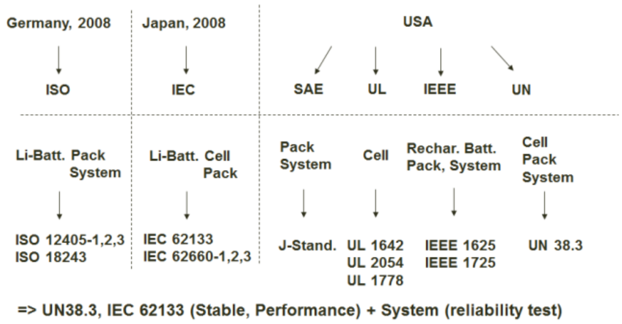

Figure 1. International standards for lithium batteries

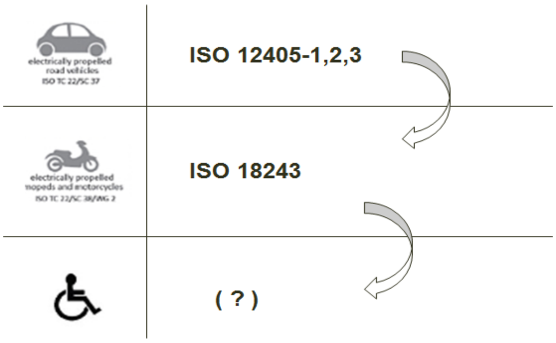

Figure 2. Process for establishing medical wheelchair standard

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II. Materials and Methods

Vibration on a lithium-ion battery mounted on a mobility scooter is low-frequency noise (≤250 Hz) caused by the excitation force generated by the friction of the tires on the road and transferred to the battery through the tires and frame while driving. The vibration level was measured with a vibration sensor (triaxial accelerometer) attached to the lithium-ion battery to identify the range of vibrations, and the random vibration levels within the given bandwidth were determined using the fast Fourier transform (FFT).

A. Vibrations

a. Experimental Environment

1) The experiments were performed in indoor and on-road driving environments. Table II outlines the experimental environments and road conditions. Vibration testing was performed in the X-, Y-, and Z-axis directions, in that order. Additionally, a temperature profile was set for different driving durations and ambient temperatures, as shown in Table. III. In consideration of the reliability test requirements under extreme temperature conditions, the maximum and minimum ambient temperatures were set at twice the usual temperatures of summer and winter months in which mobility scooters are used [4].

2) For indoor experiments, the test track (16-M & 14-M circuit; lane width: 2 m; total length: 60 m) in the Rehabilitation Engineering Research Center of the Korea Labor Welfare Corporation was used. Each test running lasted 30 min. For on-road driving experiments, the roads commonly used by people with physical disabilities, including sidewalks, bicycle lanes, and roads, were used. The experiments on sidewalks, which are most frequently used by mobility scooter users, were performed in an environment created pursuant to the Mobility Enhancement for the Mobility Impaired Act and the “Road Safety Facility Installation and Management Guidelines—Safety Facilities for People with Disabilities.” The experiments on bicycle lanes and roads were performed on those designed in compliance with the guidelines laid down in the Road Design Standards issued by the Ministry of Land, Infrastructure and Transport. All read road tests were performed for 30 min under the road conditions of cross slope of ≤2%, superelevation of ≤7 %, longitudinal slope of ≤15 %, and friction factor of 0.14–0.16.

b. Test Items

1) The test model is shown in Table I.

2) Tri-axial random vibration testing was performed, and the vibration levels were measured using a tri-axial accelerometer (Saver 3x90, Lansmont Corporation, Monterrey, CA, USA) attached to a lithium-ion battery mounted on the mobility scooter. The calibration uncertainty of this accelerometer (calibrated at 25℃ and 50% RH) was ≤0.06 G_{rms} per unit input value of 5 G_{rms} in the measurement bandwidth of 1–250 Hz.

3) Table III and Table IV present the frequency-dependent test profile of tri-axial random vibration levels of the lithium-ion battery while driving.

TABLE I. Test Model

	Electric wheelchairs	
Name	Victory-FX	Karma
Max. speed	15 km/h	10 km/h
Acceleration speed	1.2 m/s^2	1.5 m/s^2
Deceleration speed	3.8 m/s^2	3.7 m/s^2
Weight	105 kg	100 kg
Occupant weight	100 kg	100 kg
Battery charging	1C, 80 % SOC	
Picture 1		
Picture 2		

TABLE II. Test Environment

	Indoor driving	Outdoor driving
Temp. & Humidity	(23±2)℃, (45±5) %R.H.	
Speed	4～15 km/h	
Cross slope	0.1 % or less	2 % or less
Curved slope	0.1 % or less	7 % or less
End slope	0.1 % or less	15 % or less
Frictional Force	0.09～0.11	0.14～0.16
Driving Time	30 min	30 min

TABLE III. Temperature Profile during Vibration Test

Test time	Cycle of Temperature	Temperature
120 min	T_{room}	(23±2) °C
60 min	T_{min}	-20 °C
120 min	T_{room}	(23±2) °C
60 min	T_{max}	65 °C
120 min	T_{room}	(23±2) °C
480 min	Total	

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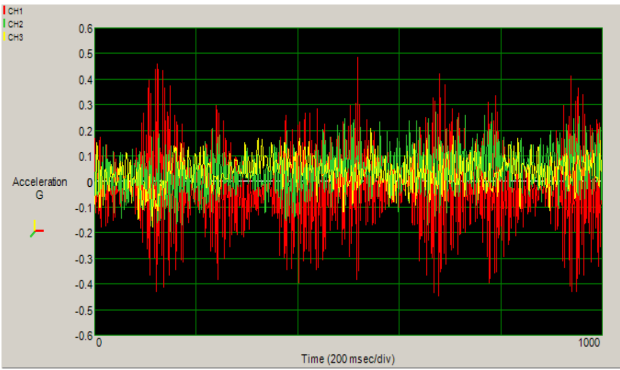
TABLE IV. TEST PROFILE OF TRIAXIAL RANDOM VIBRATION LEVELS OF THE LITHIUM-ION BATTERY WHILE DRIVING

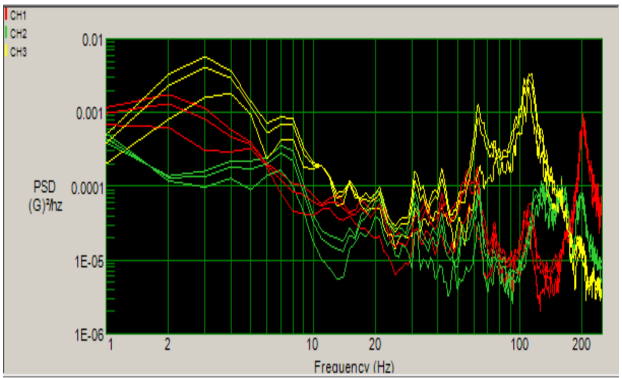
Axis	X	Y	Z
Freq. (Hz)	PSD (g^2/Hz)	PSD (g^2/Hz)	PSD (g^2/Hz)
5	0.000177609	0.0005893977	0.001236914
10	0.000047391	0.0000345278	0.001137809
20	0.000040545	0.0000495555	0.000038132
50	0.000337868	0.0004478374	0.000087719
100	0.000017964	0.0000174850	0.000018480
200	0.000000794	0.0000003972	0.000001117

c. Analysis Results

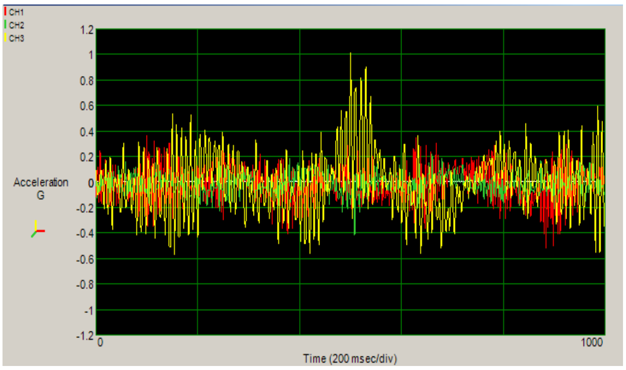
1) The curves in Figure. 3 represent the vibration levels in the time and frequency domains measured in the bandwidth of 1–250 Hz in indoor and on-road driving environments (red: X-axis; green: Y-axis; yellow: Z-axis). The graphs show higher amplitudes along the X-axis in indoor driving and higher amplitudes along the Z-axis in the on-road driving environment. Increasing random vibrations are observed in the higher bandwidth segment (100–250 Hz), which suggests a need for segmentwise vibration testing and standardization. Because the turning radius of a mobility does not generally exceed 1.2 m, the amplitude values along the Y-axis exceed those along the Z-axis in the bandwidth of more than 100 Hz.



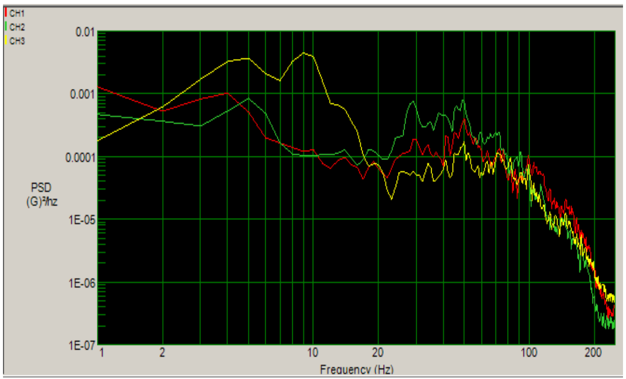
(a) Vibration level in time domain in indoor driving



(b) Vibration level in frequency domain in indoor driving



(c) Vibration level in time domain in outdoor driving



(d) Vibration level in frequency domain in outdoor driving

Figure 3. Vibration levels in the time and frequency domains while indoor-outdoor driving

B. Mechanical Shock

a. Experimental Environment

1) The mechanical shock to which the lithium-ion battery was exposed while driving was measured under the same experimental conditions as outlined in Table II. Additionally, impact conditions were set as follows: the impact condition for a tri-axial shock test while driving at the maximum driving speed of 15 km/h and the impact condition for a shock test when the wheels roll from a 0.25-cm-high curbstone [5].

b. Test Items

1) This test can be applied not only to the lithium-ion battery but also to the system mounted on the frame or rigid parts of an electric wheelchair. Table V presents the test profile for the impact exerted on the lithium-ion battery while driving. The test profile was created based on the impact levels on the battery when the wheels roll down a curbstone and those during a front collision (against a wall) while driving at the maximum speed and a side-on collision while turning. Tri-axial impact levels were measured while driving at an acceleration of 0.4 m/s^2 and maximum speed of 15 km/h, and each test was repeated 10 times on each axis. The impact pattern was half sine wave with irregular intervals, but the impact was exerted every 2.5 s for data collection and normalization purposes. The impact on the battery while rolling down or up a curbstone or external impact independent of driving was measured every 10 s with five repetitions.

TABLE V. TEST PROFILE FOR THE IMPACT EXERTED ON THE LITHIUM-ION BATTERY WHILE DRIVING

Max. Speed	15 km/h
Acceleration	4 m/s^2
Pulse width	10 ms
Pulse type	half-sine wave
Cycle	X, Y, Z = 10
Battery charging	1C, 80 % SOC

c. Analysis Results

1) Fig. 4 illustrates the triaxial impact frequency caused by collisions while driving. The average impact frequency was 30 times every 50 s, the average driving impact level was 0.667 Grms, and the average externally exerted impact level was 1.337 Grms.

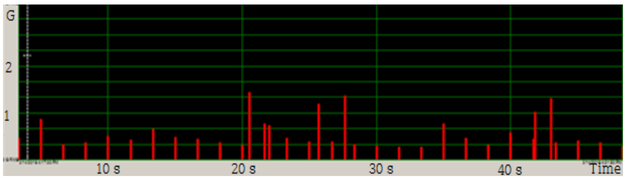


Figure 4. Vibration levels in the time and frequency domains

C. Dewing

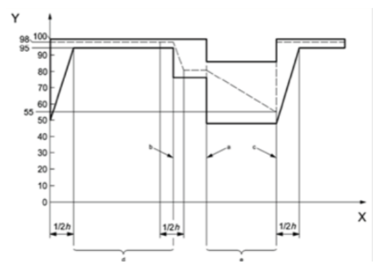
a. Test Items

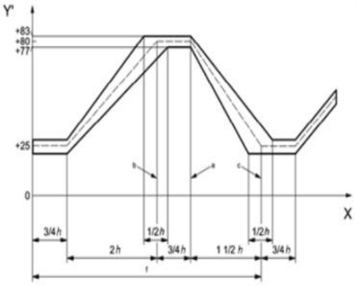
1) This test simulates the use of the system/component under high ambient humidity. This test applies to battery packs and systems. The test profile is shown in Table VI and Table VII.

TABLE VI. TEST PROFILE FOR DEWING OF LITHIUM-ION BATTERY

	Min.	Max.
Humidity	50 %	95 %
Temperature	25 ℃	80 ℃
Change time	< 30 min	
Cycle	10	
Battery charging	1C, 80 % SOC	

(a) TEST PROFILE FOR DEWING OF LITHIUM-ION BATTERY

Humidity (50 ~ 95) %	

Temperature (25 ~ 80) ℃	
Battery Charging	1C, 80 % SOC

(b) CORRELATION BETWEEN TEMPERATURE AND HUMIDITY

D. Thermal Shock

a. Test Items

1) Simulates a thermal load derived from the electric wheelchiar operations which a battery system will likely experience during its life. The test profile is shown in Table VIII.

TABLE VII. TEST PROFILE FOR THERMAL SHOCK OF LITHIUM-ION BATTERY

	Min.	Max.
Temperature	25 ℃	65 ℃
Temp. of change time	< 30 min	
Temp. of hold time	60 min	
Cycle	10	
Battery Charging	1C, 80 % SOC	

III. RESULTS

A. Vibration & Shock Testing While Driving

Test profiles were determined based on the measurements of the vibration and shock levels exerted on the lithium-ion battery mounted on a mobility scooter in indoor and on-road driving environments, and the proposed test profiles were tested and verified in a nationally accredited testing laboratory – KTC (Korea Testing Certification).

The vibrations transferred to the battery under the indicated driving conditions were found to incur no leakage, short circuit, burst, or explosion.

Impacts generated half sine waves of 10-ms pulse width with an upper- and lower-level error range of ±5%. The shocks transferred to the battery under the indicated impact conditions were found to incur no leakage, short circuit, burst, or explosion.

B. Reliability Testing for the Test Results

Robust statistics were used to validate the study results. This statistical methodology lends itself well to testing experimental results and analysis data having outliers such as vibrations and shocks. The robust validation of vibration and shock tests yielded more than 95% reliability at 10 repetitions, with Z-scores of 0.84 and 0.75, respectively [$|Z| \leq 2$ & $|Z| \fallingdotseq 0$ = the test results are very consistent or satisfactory = over 95% reliability] [6].

Proficiency testing was performed by a group of test persons on the same samples, and it was evaluated using analysis of variance (ANOVA). The ANOVA on the proficiency levels showed more than 95% reliability as well [F ratio < F critical value = H0: the test results are consistent = over 95% reliability] [7].

IV. Conclusion

On-road driving vibration and mechanical shock tests were performed on the roads frequently used by mobility scooter users, and test profiles for lithium-ion batteries were established. Additionally, the raw data for the proposed test profiles were validated with a 95% level of reliability using robust and proficiency statistics. The validated test profiles were tested and verified in a nationally accredited testing laboratory.

If the lithium-ion battery reliability test items can be added in a follow-up study based on the results of this study, it will provide great momentum to establishing safety and reliability standards for the safety and reliability of mobility scooters, greatly contributing to enhancing the traffic safety and quality of life for vulnerable road users.

Acknowledgment

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