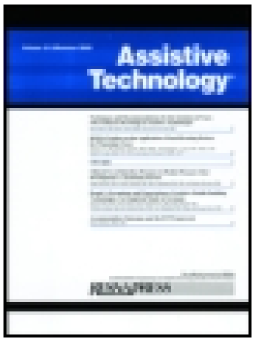

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Assessment of Physiological Performance and Perception of Pushing Different Wheelchairs on Indoor Modular Units Simulating a Surface Roughness Often Encountered in Under-Resourced Settings

Kotaro Sasaki & Karen Rispin

Assessment of physiological performance and perception of pushing different wheelchairs on indoor modular units simulating a surface roughness often encountered in under-resourced settings

Kotaro Sasaki[1] and Karen Rispin[2]

Affiliation: 1. School of Engineering and Engineering Technology, LeTourneau University

2. Department of Biology, LeTourneau University

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Abstract

In under-resourced settings where motorized wheelchairs are rarely available, manual wheelchair users with limited upper-body strength and functionalities need to rely on assisting pushers for their mobility. Because traveling surfaces in under-resourced settings are often unpaved and rough, wheelchair pushers could experience high physiological loading. In order to evaluate pushers' physiological loading and to improve wheelchair designs, we built indoor modular units that simulate rough surface conditions, and tested a hypothesis that pushing different wheelchairs would result in different physiological performances and pushers' perception of difficulty on the simulated rough surface. Eighteen healthy subjects pushed two different types of pediatric wheelchairs (Moti-Go manufactured by Motivation, and KidChair by Hope Haven) fitted with a 50-kg dummy on the rough and smooth surfaces at self-selected speeds. Oxygen uptake, traveling distance for six minutes, and the rating of difficulty were obtained. The results supported our hypothesis, showing that pushing Moti-Go on the rough surface was physiologically less loading than KidChair, but on the smooth surface the two wheelchairs did not differ significantly. These results indicate that wheelchair designs to improve pushers' performance in under-resourced settings should be evaluated on rough surfaces.

Introduction

The demands for wheelchairs in under-resourced settings are high, and have not been adequately met due partly to inappropriate wheelchair designs and poor distribution structures and systems (Pearlman et al., 2008; Pearlman, Cooper, Zipfel, Cooper, & McCartney, 2006). Manual wheelchairs provided may be unsuitable for indoor or outdoor use and in many cases rejected by users (Mukherjee & Samanta, 2005). In general, roads and pathways in under-resourced settings are uneven and rough. Such conditions not only lead to a shorter life span of wheelchairs (Toro, Garcia, Ojeda, Dausey, & Pearlman, 2012) but also physiologically tax wheelchair users due to high rolling resistance (Cowan, Nash, Collinger, Koontz, & Boninger, 2009; Koontz et al., 2005; Wolfe, Waters, & Hislop, 1977). A recent study has shown that wheelchair users' physiological responses during self-propulsion on rough outdoor surfaces are influenced by the types of wheelchair, indicating the importance of wheelchair design to reduce physiological cost (Rispin & Wee, 2015). Thus far, many studies on physiological aspects of manual wheelchair locomotion have primarily focused on users who are capable of self-propulsion with sound upper-body strength and functionalities (e.g., Cooper, Boninger, Cooper, Robertson, & Baldini, 2003; Keyser, Rodgers, Gardner, & Russell, 1999; G. Mukherjee & Samanta, 2001; L. H. van der Woude, Veeger, Dallmeijer, Janssen, & Rozendaal, 2001; L. H. V. van der Woude, Formanoy, & de Groot, 2003; Vegter, de Groot, Lamoth, Veeger, & van der Woude, 2014).

In under-resourced settings where motorized wheelchairs are not readily available, wheelchair users who have limited upper-body strength and functionalities require assisting care-givers to push the wheelchair to generate propulsion. Even the strongest self-propelling wheelchair users occasionally need to be pushed when they get stuck or become tired while moving on rough surfaces. In under-resourced settings, such assisting pushers may themselves be under stress economically or physically (Borg, Lindström, & Larsson, 2011; Lysack, Wyss, Packer, Mulholland, & Panchal, 1999). Therefore, reducing the physiological loading on pushers is important to increase the mobility of wheelchair users, particularly those who have limited upper-body strength. Pushing wheelchairs on rough surfaces is not easy due to increased rolling resistance, and is likely to increase the physiological cost in pushers. Furthermore, the extent of the potential increase in the physiological cost of pushing may be different in different types of wheelchairs. In order to evaluate wheelchairs for under-resourced settings, testing in similar conditions to the setting of use is essential (Hersh, 2010; Ikeda, Grabowski, Lindsley, Sadeghi-Demneh, & Reisinger, 2014; Reeve et al., 2013). However, evaluating pushers' performance in response to different wheelchair designs on outdoor rough surfaces may produce inconsistent results due to different weather conditions, terrains and ground cover.

Previous studies have analyzed the influence of traveling surface conditions on wheelchair user performance such as endurance and physical stress, demonstrating that surface differences have significant influences on users' performance (Cowan et al., 2009; Koontz et al., 2005; L. H. V. van der Woude, Geurts, Winkelman, & Veeger, 2003; Wolfe et al., 1977). Also, attempts have been made to develop benchmark obstacle courses for user skills tests (Routhier, Desrosiers, Vincent, & Nadeau, 2005; Routhier, Vincent, Desrosiers, Nadeau, & Guerette, 2004) and to quantify the firmness or rolling resistance of different surfaces (Chesney & Axelson, 1996; L. H. V. van der Woude, Geurts, et al., 2003). However, the surface materials (e.g., carpets, tiles) or obstacle conditions examined in those studies may rarely be seen in under-resourced settings where roads are often rough with pebbles, cracks and depressions. Also, the standard tests or conditions for wheelchair users may not be directly applicable to pushers because of the differences in physical capacities and the biomechanics of wheelchair propulsion. Only a few studies have been conducted on wheelchair pushers or caregivers (Choi, Lee, Lee, & Kwon, 2015; Van Der Woude, Van Koningsbruggen, Kroes, & Kingma, 1995), and no standard tests for wheelchair pushers' performance were found.

The standard practice for quantifying road roughness for a vehicle defines the roughness index as the accumulated vertical displacement of a wheel for a given horizontal traveling distance (ASTM E1926). Duvall and colleagues applied this roughness index to quantify the surface roughness for wheelchairs with 2.5-inch wheelchair casters (Duvall et al., 2013). They created 16-feet artificial indoor rough pathways with several roughness indices using wooden boards with specified board widths and gaps between boards, and evaluated the vibrations that wheelchair users sustain. Thus far, their study is the only one quantifiable source of surface roughness for wheelchairs. Therefore, the current study adopted the wheelchair roughness index defined in their study to build modular rough surface units for indoor use in order to enable consistent and repeatable evaluations of pushers' performance.

Physiological performance may be evaluated using a standardized test such as the six-minute walk test (Guyatt et al., 1985). This test is commonly prescribed to assess cardiopulmonary functions of various cadres of subjects by measuring the traveling distance in six minutes on a 30-meter pathway (McDonald et al., 2010; Steffen, Hacker, & Mollinger, 2002). During the six-minute walk (pushing) tests, oxygen uptake may also be monitored as another index of physiological performance and loading, which has been commonly used for aerobic exercise (G. Mukherjee & Samanta, 2001; Nieman et al., 2007; Salvi, Hoffman, Sabharwal, & Clifford, 1998). In addition to physiological performance, pushers' subjective rating and comments such as the ease or difficulty of pushing may provide insight into improving wheelchair design.

Therefore, the objectives of this study were: (1) to enable consistent evaluation of wheelchair performance on rough surfaces by developing modular rough-surface units with quantifiable and repeatable roughness for six-minute wheelchair pushing tests; (2) to test a hypothesis that different types of wheelchairs result in detectable differences in the physiological cost and the rating of pushing on the developed rough-surface pathway.

Methods

Modular rough-surface units to generate indoor rough pathways

The modular rough surface units were created to simulate surface roughness as defined by Duvall and colleagues (Duvall et al., 2013) who specified roughness indices for wheelchairs with 2.5-inch casters. In the current study, we selected one of the roughness indices (1.36 in/ft) for the modular units in attempt to simulate an unpaved surface with pebbles and depressions, or a rough concrete surface with gaps and cracks often encountered in under-resourced settings. Although outdoor ground surface conditions may vary considerably, the roughness was selected based on authors' study and experience in Kenya (e.g., Funk, Thiessen, Wright, Andrysek, & Rispin, 2016; Rispin & Wee, 2014, 2015).

Since installing a permanent 30-meter rough pathway inside a building is often not practical, we aimed to build modular rough-surface units that can be easily set and removed. To generate a rough pathway, 16 wooden boards (95.3 cm by 15.2 cm by 1.9 cm each) were attached to two parallel polyvinyl chloride pipes (3 m in length, 6 cm in diameter) using rubber strips wrapped around the pipes and stapled on the boards. Spacers were placed between the boards to ensure the space in-between was fixed at 5 cm (Figure 1). This configuration of the board width (15.2 cm) and gap space (5 cm) generated the roughness index of 1.36 (in/ft) for a wheelchair defined by Duvall and colleagues (Duvall et al., 2013). A total of seven modular units were built, which resulted in a 21-meter pathway when placed in series. The additions of a 4.5-meter smooth turnaround at the both ends of the path made a 30-meter pathway for six-minute walk tests. This pathway was set up in a three-meter wide hallway inside a building. A smooth 30-meter pathway was also set up on a hallway surfaced with linoleum in the same building in order to compare the influence of surface types on pushers' physiological cost and rating.

Participants

A sample of convenience was obtained by the university students randomly inviting other students without disabilities to volunteer for the study. The volunteers agreed and signed subject consent forms according to the protocols for this study approved by the university institutional review board before participating in the experiments. Participants were free to withdraw at any time.

Physiological performances and rating of difficulty

A repeated measures study design was utilized in which each participant pushed two types of wheelchairs on both surfaces. This total of four trials were performed in a randomized order with a minimum three-minute resting period between trials. During the resting period, heart rate was monitored and participants continued resting until their heartrate returned to their initial non-exercise heart rate taken while sitting and resting before the first timed walk was performed. On both the smooth and rough pathways, participants were asked to push wheelchairs at a self-selected speed for six minutes as described in the protocol for the six minute timed walk test (ATS Committee on Proficiency Standards for Clinical Pulmonary Function Laboratories, 2002). Distance traveled in six minutes was measured using a measuring survey wheel (DW-500, US Tape, Pennsburg, PA).

Oxygen uptake data (in ml/min/kg) were recorded every 30 seconds using a portable metabolic monitor (FitMate PRO, COSMED, Rome, Italy) during the walk test. After the trial, data were downloaded and the mean value during the last two minutes of the trial was calculated. Oxygen uptake from the last two minutes was utilized because preliminary results had indicated that the oxygen uptake pattern during the last two minutes was characteristic of aerobic energy use.

Pushers' subjective ratings of difficulty of pushing were obtained using the visual analog scale (VAS) after each trial. A 100-mm VAS was used, with the left-hand end being "Poor" indicating "extremely difficult to push" and the right-hand end being "Excellent" indicating "extremely easy to push." Also, letter grades from A to E/F were indicated under the VAS scale as guidance for the subjects to determine the rating (Figure 2). The VAS score was quantified by measuring the length from the left end to the mark made by the subject on the scale. Therefore, a low VAS score indicates that the subject felt difficulty in pushing during the trial. In addition, pushers' comments on why the trial was difficult were recorded and similar comments made by three or more subjects were identified.

Wheelchairs

The two types of pediatric wheelchairs used in this study were KidChair by Hope Haven Inc. (Rock Valley, IA) and Moti-Go manufactured by Motivation (Bristol, UK) (Figure 3a, b). Both wheelchair types are commonly distributed in under-resourced settings. Wheelchairs were fitted with a 50-kg ISO standards test dummy (ISO 7176-11:2012). Table 1 shows several parameters of the wheelchairs with the dummy.

Statistical analysis

Two-way repeated measures ANOVAs were performed to test our hypothesis at a significant level of 0.05, with the independent variables being the surfaces and wheelchair types, and dependent variables being oxygen uptake, traveling distance during the six-minute trials, and the VAS scores. When significant differences were found, post-hoc analyses were performed using Tukey's multiple comparisons. Minitab statistical software (version 17, Minitab Inc., State College, PA) was used for the analyses.

Results

Modular rough-surface units were successfully utilized to construct an indoor rough pathway with a known and repeatable roughness. The modular units (25 kg, three-meter long each) were easily carried by two people and linked together using duct tape to set up a 30-meter pathway on a hallway. When not in use, the set of units was compactly stored in a vertical position requiring only a one-square meter floor space and held together using elastic cords (Figure 4).

Eighteen subjects (eleven males and seven females, mean age 20.6 ± 2.3, mean height 174.4 ± 10.6 cm, mean body mass 70.4 ± 12.5 kg) completed the four trials pushing the two types of wheelchairs on the smooth and rough surfaces. None withdrew from the study.

Repeated measures ANOVA indicated that the main effects of the two independent variables, surface and wheelchair type, both differed significantly (Table 2). ANOVA indicated significant interaction between the wheelchair and surface factors in traveling distance and VAS score (Table 2). Tukey's multiple comparisons of means indicated that on the rough surface pushing the Moti-Go wheelchair compared to KidChair resulted in significantly lower oxygen uptake (14.7 vs. 16.0 ml/min/kg), longer distance traveled (393.5 vs. 356.3 m), and higher VAS scores (69.6 vs. 50.5 mm) (Figure 5). In contrast, on the smooth surface the performance differences and the VAS scores between the two wheelchairs were not statistically significant (Moti-Go vs. KidChair: 13.9 vs. 14.5 ml/min/kg; 399.5 vs. 391.5 m; and 74.7 vs. 80.8 mm, respectively, Figure 5). The comparison results also showed that the physiological performance and rating of pushing KidChair significantly deteriorated on the rough surface compared to the smooth surface (Smooth vs. Rough: 14.5 vs. 16.0 ml/min/kg; 391.5 vs. 356.3 m; and 80.8 vs. 50.5 mm, respectively, Figure 5). In contrast, Moti-Go was insensitive to the surface type (Smooth vs. Rough: 13.0 vs.14.8 ml/min/kg; 399.5 vs. 393.5 m; and 74.7 vs. 69.6 mm, respectively, Figure 5).

The most frequently observed comment on difficulty in pushing on the rough surface was that pushing KidChair was rough or bumpy (seven subjects), followed by the comment related to the difficulty of "clearing bumps" with the front casters in KidChair (three subjects). On the smooth surface, subjects commented that Moti-Go was wobbly, unstable, or shaky (five subjects). In contrast, there were few negative comments on pushing KidChair on the smooth surface.

Discussion

The primary objectives of this study were to enable consistent evaluations of physiological performance of pushing wheelchairs designed for under-resourced settings, and to examine the performance using different wheelchairs on surfaces with different roughness. Modular rough-surface units were built to provide a repeatable and quantifiable rough surface for the evaluations. The instructions for building the modular units are available at http://www.letu.edu/opencms/opencms/_Academics/Arts-Science/biology/Wheels/MRSU/. The developed modular units can offer an alternative to the data collection on outdoor surfaces that is prone to include large uncertainty, and the results in this study comparing two wheelchair types confirmed the functionality of these units in enabling a study that can discriminate between wheelchair types. The roughness generated in the modular units was based on the study by Duvall and colleagues (Duvall et al., 2013), where the surface roughness indices of several outdoor and artificial indoor surfaces were quantified. Although only one surface roughness was selected in this study (1.36 in/ft), the roughness can be easily modified by changing the board width and the space between the boards (Duvall et al., 2013). The roughness index might not be the only way to quantify surface roughness, but it is a useful measure to create consistent and quantifiable artificial indoor rough surfaces to measure pushers' physiological responses.

This study focused on the physiological cost and rating of pushing wheelchairs on rough surfaces. Previous studies on the physiological cost have more often focused on self-propelling wheelchair users with good upper-body strength, and have shown increased physiological loading on the surfaces with high rolling resistance (Cowan et al., 2009; Koontz et al., 2005; Wolfe et al., 1977). Compared to users' performances, little is known about pushers' physiological responses. A study of pushers' performance on different ramp slopes has shown decreased self-selected pushing speeds with increased slope angles (Choi et al., 2015). However, no studies have examined physiological responses to pushing wheelchairs on rough surfaces. The physiological cost to pushers is of special importance to wheelchair users in under-resourced settings where ground surfaces are often unpaved and rough. Since manual wheelchair locomotion on rough surfaces is not easy and powered wheelchairs are hardly available in those environments, users often need to rely on assisting pushers for mobility. Therefore, wheelchair designs in under-resourced settings should take account of not only users but also pushers.

Our results showed that wheelchair pushers could sustain higher physiological cost dependent on the types of wheelchairs they push. Significant differences in pushers' oxygen uptake, traveling distance, and visual analog scale (VAS) scores were found between the two wheelchairs on the rough surface, with the Moti-Go wheelchair outperforming KidChair. In contrast, the two wheelchairs showed much less difference in performance on the smooth surface. A previous study on physiological cost and rating of self-propelling wheelchair users also identified significant differences among different wheelchairs on rough outdoor surface (Rispin & Wee, 2015). These results imply the importance of testing the performance on rough surfaces to evaluate wheelchairs for use in under-resourced settings. Designing with the intention of reducing the physiological loading of traveling on rough surfaces for assistants pushing wheelchair would enable easier travel and improve the mobility of all wheelchair users who occasionally or frequently need to be pushed.

There exist some noticeable design differences between the Moti-Go and KidChair that might have led to the differences in physiological performance and rating, including the wheel diameter, wheelbase and handle height (Table 1). Qualitatively, a wheel with a smaller diameter sustains larger horizontal reaction forces from "bumps" on the ground due to a larger angle of attack. Therefore, pushing KidChair with smaller wheels and front casters would be expected to be rougher. Also, KidChair has two front casters in contrast to one caster in Moti-Go, which would make KidChair get caught by bumps more frequently and sometimes unevenly. These differences might be reflected in the comments on KidChair made by our subjects that pushing was "bumpy" on rough surface. The shorter wheelbase of KidChair would also work against pushing on rough surface, because in order to clear bumps at the front caster(s) the wheelchair needs to be back-tilted to a greater extent. Such disadvantage may be related to the subjects' comment on the difficulty in lifting front casters. As for the handle height, a higher handle position would work against pushing on rough surface. This is because horizontal pushing force at the handle has a large moment arm at the wheel-ground contact point, which in turn presses the front caster on the ground with a larger force (Hamilton et al., 2015). However, our subjects left no comments on difficulty related to the handle height in Moti-Go. It is possible that the longer wheelbase in Moti-Go might have nullified the adverse effects of handle height, reducing the downward force by the front caster. More detailed and quantitative analyses including the biomechanics of wheelchair pushing (e.g., van Der Woude et al., 1995) and force measurements are necessary to identify the effects of the design parameters on physiological performance and rating. It has be noted that the improvement of wheelchair design needs to take account of both users and pushers, although general guidance for wheelchair design parameters for rough surfaces might be similar for both groups. For example, wheelchairs with large rims could be energetically more demanding for users to propel themselves (Guo, Su, & An, 2006; L. H. van der Woude et al., 1988). Also, too large rims would cause elevated users' shoulder positions during propulsion, which might lead to high loads on the shoulder joints and increase injury risks (Alm, Saraste, & Norrbrink, 2008; Boninger et al., 2003; Brose et al., 2008). Therefore, the optimal balance in design parameters should be pursued for both users and pushers.

Future work

This study created rough surface units with the roughness index of 1.36 in/ft specified in the study by Duval and colleagues (2013) where this roughness was rated most uncomfortable by wheelchair users. The Moti-Go wheelchair did not show significant differences in physiological cost and rating between this rough surface and smooth surface, which distinguished the wheelchair from KidChair that was more sensitive to surface roughness. This information has important implications for improving wheelchair design. However, the Moti-Go wheelchair might exhibit the differences if pushed on the surfaces with different roughness. Also, on outdoors surfaces many different slope angles and terrains are encountered. It is expected that pushing wheelchairs on varying roughness and terrains would result in different physiological responses. The current study used a single rough surface that would simulate the overall characteristics of unpaved dry surfaces with pebbles and depressions or rough concrete surfaces with gaps and cracks seen in under-resourced settings. However, the created indoor surface does not represent different types of surfaces covered with puddles, mud, loose gravel and sand, which are also prevalent in under-resourced settings. Therefore, future studies should be directed toward examining the sensitivity of wheelchairs to different roughness, terrains and surface conditions. For example, different roughness indices (Duvall et al., 2013) for the modular units could be tested as sensitivity analysis to observe the roughness at which the performance of Moti-Go or KidChair begins to deteriorate. In addition, placing ramps under the modular units would provide in-depth insight into pushers' performance for improvement of wheelchair designs.

The VAS scores measured in this study resulted in the same trend as the physiological performance, showing that KidChair is more difficult to push than Moti-Go on the rough surface and that pushing KidChair is significantly more difficult on the rough surface than on the smooth surface (Figure 5). The consistency between the VAS score and physiological performance on the rough surface may indicate that with further validation these questions potentially have a possible use as one of the primary indices of evaluating wheelchairs without using any testing devices and equipment (e.g., a metabolic monitor). Such simple ratings would increase the number of responses and evaluations from subjects who use or push wheelchairs in under-resourced settings on various types of outdoor surfaces encountered in actual real-life environments, which is important to improve the wheelchair design. Therefore, one of our future studies would be directed toward validating the relationship between physiological performance and VAS scores in various tests.

Recommendations

A limitation of this study is that the tire pressure was not strictly controlled, although the tires showed no visual evidence of under-inflation or deformity between or within trials. The KidChair has solid tires, but the Moti-Go has inflatable tired with a recommended tire pressure of 55 psi and this was not measured before each trial. Low tire pressure increases the rolling resistance of wheelchairs (Kwarciak, Yarossi, Ramanujam, Dyson-Hudson, & Sisto, 2009).

Therefore, controlling and monitoring tire pressure before and during data collection should be enforced in future studies.

Conclusion

The modular surface units developed in this study allowed easy setup and removal of a rough pathway inside a building to evaluate wheelchair pushers' physiological performance and rating in six-minute walk (pushing) tests. The surface roughness used in this study was sufficient to statistically differentiate pushers' performance and rating while pushing two different wheelchairs. The differences in pushers' performance indicate the importance of wheelchair evaluation on rough surfaces. These results could facilitate design improvement for wheelchairs intended for use in under-resourced settings, where pushers are often responsible for providing mobility for those who have limited upper-body strength and functionalities.

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Fig. 1 Rough pathway created with seven modular units placed on a hallway.

Fig. 2 Visual analog scale (VAS) of ease.

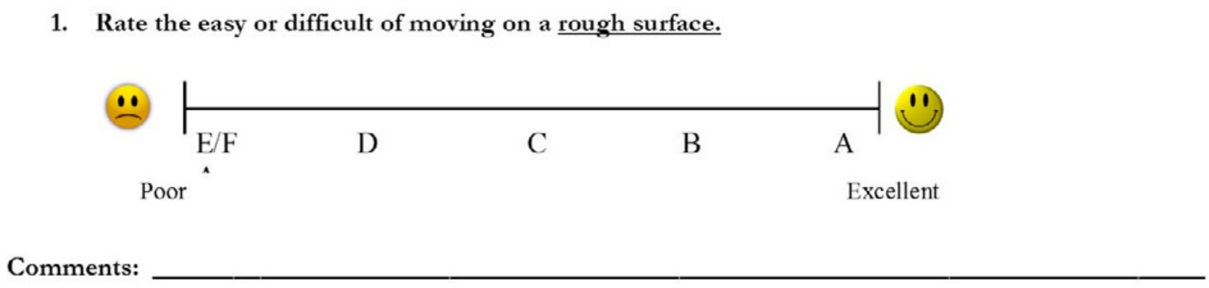

Fig. 3 (a) Hope Haven KidChair and (b) Motivation Moti-Go with a 50-kg dummy.

(a) (b)

Fig. 4 Modular units stored in a laboratory.

Fig. 5 Mean oxygen uptake, traveling distance and visual analog scale (VAS) of ease during the six-minute walk tests on the smooth and rough surfaces using two different wheelchairs.

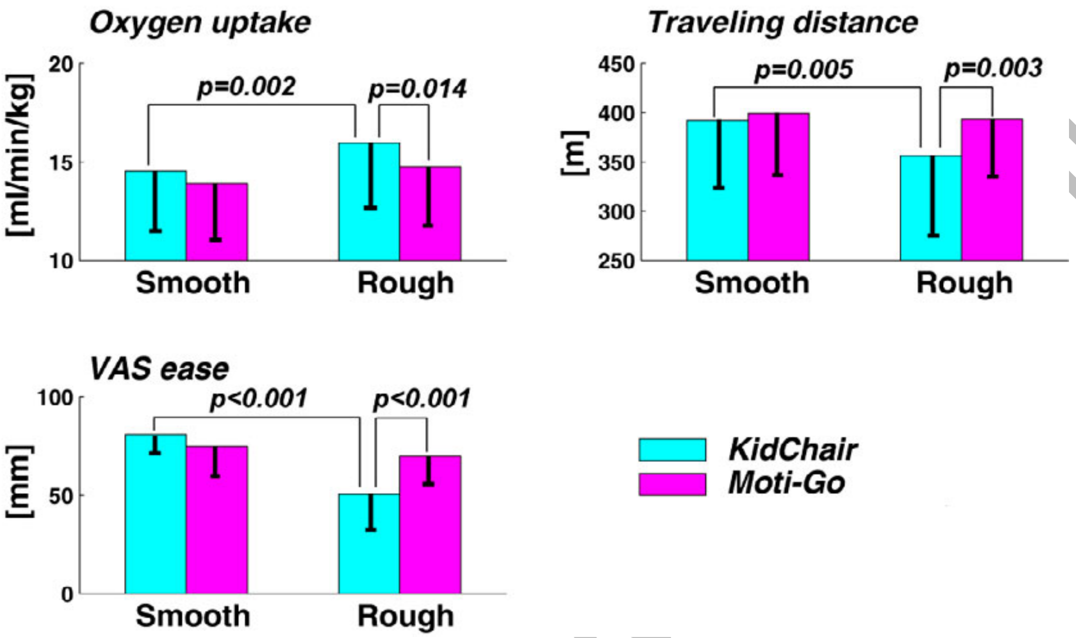

Table1: Parameters of the KidChair and Moti-Go wheelchairs. The mass includes the 50-kg dummy. The handle height is the vertical distance from the ground. COM is the horizontal position of the mass center anterior to the wheel axle. Note that KidChair has two front casters and Moti-Go has one.

Wheelchair	***Mass* (kg)**	***Wheel diameter* (cm)**	***Caster diameter* (cm)**	***Wheelbase* (cm)**	***Handle height* (cm)**	***COM* (cm)**
KidChair	70.2	55.9	19.1	50.8	88.5	16.8
Moti-Go	73.6	66.0	21.6	68.6	97.5	16.0

Table 2 Repeated measures ANOVA results for the main and interaction effects of wheelchair types and surfaces on oxygen uptake, traveling distance and visual analog scale (VAS) for ease of push during the six-minute walk tests on the smooth and rough surfaces using two different wheelchairs.

Test	Wheelchair factor	Surface factor	Wheelchair×Surface
Oxygen uptake	$F(1,51) = 11.77$, $p = 0.001$	$F(1,51) = 20.04$, $p < 0.001$	$F(1,51) = 1.09$, $p = 0.302$
Traveling distance	$F(1,51) = 10.07$, $p = 0.003$	$F(1,51) = 8.37$, $p = 0.006$	$F(1,51) = 4.22$, $p = 0.045$
VAS ease of push	$F(1,51) = 6.02$, $p = 0.018$	$F(1,51) = 44.44$, $p < 0.001$	$F(1,51) = 22.61$, $p < 0.001$