Evaluation of wheelchair pushing performance on simulated rough pathways in under-resourced settings created with indoor modular units

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ABSTRACT

In under-resourced settings, wheelchair users with limited upper body strength and functionalities often need to be pushed for their mobility. However, pushing wheelchairs in such environments has not been well investigated. This study aimed first to develop modular rough-surface units for indoor use that simulate rough surface conditions to evaluate wheelchairs in under-resourced settings. The second objective was to test a hypothesis that pushing two different wheelchairs would result in different physiological performances and pushers' subjective rating of difficulty on the simulated rough surface. Eighteen non-disabled subjects pushed two wheelchairs 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 pushing difficulty on the visual analog scale were obtained. The results supported our hypothesis, showing that pushing one wheelchair (Moti-Go manufactured by Motivation) on the rough surface resulted in lower oxygen uptake, greater traveling distance, and lower difficulty rating than pushing the other wheelchair (KidChair by Hope Haven). In contrast, these performances were indifferent between the two wheelchairs on a smooth surface. These results indicate that wheelchair designs to improve pushers' performance in under-resourced settings should be evaluated on rough surfaces.

BACKGROUND

Wheelchair users who have limited strength and functionalities in their upper body require assistance to generate propulsion. In under-resourced settings where motorized wheelchairs are not readily available, assisting care-givers are often responsible for pushing wheelchairs. Because traveling surfaces in under-resourced settings are often unpaved and rough, wheelchair pushers could experience high physiological loading. It is known that wheelchair users are physiologically taxed when generating propulsion on rough surfaces due to increased rolling resistance (Cowan, Nash, Collinger, Koontz, & Boninger, 2009; Koontz et al., 2005; Wolfe, Waters, & Hislop, 1977). If wheelchair pushers experience high physiological loading, the design of wheelchairs for under-resourced settings should take account of not only users but also pushers. However, evaluating pushers' physiological loading (or performance) in response to different wheelchair designs on outdoor rough surfaces may generate inconsistent results due to different weather conditions, terrains and ground cover. In order to systematically evaluate the performance of wheelchairs for under-resourced settings, consistent and quantifiable rough surfaces need to be provided.

PURPOSE

The purpose of this study was two-fold: (1) to enable consistent evaluation of wheelchair performance on rough surfaces by developing modular rough-surface units with repeatable and quantifiable roughness for indoor use to measure the physiological performance of wheelchair pushers; and (2) to test a hypothesis that pushing different types of wheelchairs results in detectable differences in the physiological performance on the developed rough-surface pathway. Physiological performance was defined as the traveling distance and oxygen uptake during six-minute walk (push) tests. In addition, pushers' subjective ratings of difficulty in pushing were examined.

METHODS

<u>Modular rough-surface units</u>

Sixteen 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. This configuration of the board width (15.2 cm) and space (5 cm) was based on the study by Duvall and colleagues (Duvall et al., 2013) that specified the "roughness index" to quantify surface roughness. The roughness index used in this study was equivalent to 1.36 (in./ft) in their study. 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 to be used 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.

Wheelchairs

The two types of wheelchairs used in this study were KidChair by Hope Haven Inc. (Rock Valley, IA) and Moti-Go manufactured by Motivation (Bristol, UK). 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.

Table 1: 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. Horizontal 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.

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

Subjects

Eighteen non-disabled students at LeTourneau University volunteered for the study (age 20.6 ± 2.3 years old, height 174.4 ± 10.6 cm, body mass 70.4 ± 12.5 kg). The volunteers agreed and signed subject consent forms according to the protocols for this study approved by LeTourneau University Institutional Review Board before participating in the experiments. Participants were free to withdraw at any time.

Physiological performances and rating of difficulty

On both the smooth and rough pathways, participants were asked to push the two wheelchairs in a randomized order 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). A minimum three-minute resting period was prescribed between trials. Distance traveled (DW-500, US Tape, Pennsburg, PA) during six minutes, and oxygen uptake (FitMate PRO, COSMED, Rome, Italy) during the last two minutes, which was considered as aerobic energy use based on our preliminary results, were obtained. The ratings of pushing difficulty were measured using the visual analog scale (VAS) after each trial. A 100-mm VAS was used, with the left-hand end indicating "extremely difficult to push" and the right-hand end being "extremely easy to push." 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.

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 and the VAS scores during the six-minute trials. 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

The modular units (25 kg, three-meter long each) were successfully utilized to construct an indoor rough pathway. The units could be easily carried by two people and linked together using duct tape to set up a 30-meter pathway on a hallway (Figure 1). 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 1: Modular units placed on a hallway.

Physiological performances and rating of difficulty

Repeated measures ANOVA indicated that the main effects of the two independent variables, surface and wheelchair type, both differed significantly. ANOVA indicated significant interaction between the wheelchair and surface factors in traveling distance and VAS score. Tukey's multiple comparisons of means indicated that on the rough surface pushers had significantly lower oxygen uptake, longer distance traveled, and higher VAS scores when pushing the Moti-Go wheelchair than pushing KidChair (Figure 2). In contrast, on the smooth surface the performance differences and the VAS scores between the two wheelchairs were not statistically significant. The comparison results also showed that the physiological performance and rating of pushing KidChair were significantly deteriorated on the rough surface compared to the smooth surface, while Moti-Go was insensitive to the surface type (Figure 2).

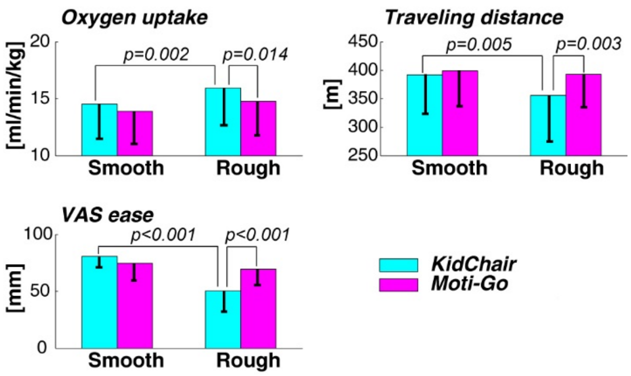

Figure 2: Mean and standard deviation values of oxygen uptake, traveling distance and visual analog scale (VAS) of ease during the six-minute walk tests on the smooth and rough surfaces using two different wheelchairs.

DISCUSSION

The primary objective of this study was to develop modular rough-surface units that provided a repeatable and quantifiable rough surface which could be used to evaluate pushers' performance using different wheelchairs. It is important to test any assistive technologies and devices in similar conditions to the setting of use (Hersh, 2010; Ikeda, Grabowski, Lindsley, Sadeghi-Demneh, & Reisinger, 2014; Reeve et al., 2013). However, repeatable testing of wheelchairs for under-resourced settings might be challenging because surface roughness is different in different locations, and outdoor data collection is extremely challenging in inclement weather. The developed modular units can offer an alternative to outdoor data collection, 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.

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 rough surfaces (Cowan et al., 2009; Koontz et al., 2005; Wolfe et al., 1977). The physiological cost to pushers is of special importance to wheelchair users in under-resourced settings where powered wheelchairs are often not available. Even the strongest wheelchair users occasionally get stuck or become tired while moving on rough surfaces, and the users with limited upper-body strength in such environments 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.

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 2). 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, 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.

Future work also includes to investigate how wheelchair parameters (e.g., Table 1) influence pushers' performances. For example, wheel base, handle height, and the location of mass center affect the magnitude of push force (Hamilton et al., 2015). Measuring such forces and assessing the biomechanics of pushing would be required to optimize the parameters.

A limitation in this study is that the pushing tests were conducted on the horizontal surfaces only, and only at one roughness setting. On outdoors surfaces many different slope angles, degrees of roughness and deformability are encountered. It is expected that pushing wheelchairs on varying terrains, roughness and deformability would result in different physiological responses. Therefore, whether the differences between the two wheelchairs found in this study remain unchanged on different terrains is unknown. Since the outdoor terrains are diverse, future studies should include different terrains. For example ramps could be placed under the modular units to evaluate pushers' performance for improvement of wheelchair designs.

CONCLUSION

Modular surface units that systematically simulate the roughness of outdoor surface conditions were developed. These modular units allowed easy setup and removal of a rough pathway inside a building to evaluate wheelchair pushers' physiological performance and rating in six-minute walk (push) tests. The surface roughness used in this study was sufficient to statistically differentiate pushers' performance and rating while pushing two different wheelchairs. 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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