## ORIGINAL ARTICLE

# Effects of Wheelchair Mass on the Physiologic Responses, Perception of Exertion, and Performance During Various Simulated Daily Tasks

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ABSTRACT. Sagawa Y Jr, Watelain E, Lepoutre F-X, Thevenon A. Effects of wheelchair mass on the physiologic responses, perception of exertion, and performance during various simulated daily tasks. Arch Phys Med Rehabil 2010;91: 1248-54.

**Objective:** To verify whether additional manual wheelchair mass above a critical level would produce, during many daily tasks, an increase in physiologic parameters, an increase in the perceived exertion, and a decrease in performance.

**Design:** A repeated-measurement design.

**Setting:** Six standardized tests thought to mimic daily activities.

**Participants:** Volunteers (N=21), 8 men with spinal cord injuries (SCIs; mean age,  $34\pm12y$ ; range, 19-56y) and 13 able-bodied persons (11 men and 2 women; mean,  $24\pm5y$ ; range, 18-37y).

**Interventions:** Random additional masses ("0", 1, 2, 5kg) were placed under the seat of a multisport manual wheelchair (mass approximately 10kg) out of the subject's field of vision.

**Main Outcome Measures:** Energy expenditure (EE; total  $o_2$  consumed), heart rate (total number of beats), perceived exertion (visual analog scale), and performance (seconds to execute a sprint test) were measured.

**Results:** For all tests, there was no significant effect of mass found for either group for the EE, heart rate, and performance. In addition, for all tests, no significant effect of mass was found for the SCI group for the visual analog perceived exertion. However, for the able-bodied group, the added mass had a significant effect for the visual analog perceived exertion (F=6.11; P=.02) in the Stop-and-Go test. A post hoc Tukey test showed a significant difference between the 0kg and 5kg mass conditions (P<.01; d=.8), between 1kg and 5kg (P=.02; d=.6), and between 2kg and 5kg (P=.01; d=.6).

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**Conclusions:** Based on these findings, it can be concluded that, under the conditions of this study, additional mass (up to 5kg) loaded on a multisport manual wheelchair does not seem have any effect on EE, heart rate, or performance and has a minor effect on the visual analog perceived exertion evaluated in many activities of daily living.

Key Words: Biomechanics; Rehabilitation; Wheelchairs.

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**M**ANUAL WHEELCHAIR propulsion is associated with great physical strain and mechanical loading of the musculoskeletal system.<sup>1-9</sup> This can be partly explained by the low mechanical efficiency (ie, relationship between physiologic energy expended and mechanical energy produced) of MW propulsion, which rarely exceeds 11%.<sup>10-12</sup>

Inertia (ie, the resistance to set a object in motion) and the rolling resistance of the MW are the major opposing forces and are influenced by such factors as overall mass; frame design; and wheel, tire, and wheel bearing characteristics. For this reason, the mass of everyday and sport MWs has been reduced dramatically. Changes in frame construction materials from traditional stainless steel to other materials (eg, aluminum, titanium, carbon fiber, and other alloys) have had a strong impact on the mass, design, strength, and durability of MWs.<sup>13-17</sup> Such materials sometimes dramatically increase the cost of MWs. Hilbers and White<sup>18</sup> investigated physiologic responses of

Hilbers and White<sup>16</sup> investigated physiologic responses of persons with SCI in the propulsion of a conventional MW (18.9kg) and a sports MW (9.8kg). They found that the energy cost of propelling a sport MW at a specific velocity was 17% less than the cost of propelling a conventional MW. The greater efficiency of the sports MW was attributed to differences in MW design rather than the total mass of the MW.

Beekman et al<sup>19</sup> found that when persons with paraplegia or tetraplegia propelled an ultralight MW (12.2kg), the speed and distance traveled were greater than that for a standard MW (20kg), while  $\dot{V}o_2$  was less only in subjects with paraplegia. Still, the absence of any changes in  $\dot{V}o_2$  for the subjects with tetraplegia might be explained by their limited functional capacity.<sup>20</sup> Like Hilbers and White,<sup>18</sup> they explained that a number of MW factors could account for the relative efficiency of the ultralight MW compared with the standard MW. These factors include the geometry and stiffness of the frame, the air

List of Abbreviations

able-bodied
carbon dioxide
energy expenditure
manual wheelchair
oxygen
spinal cord injury
oxygen consumption per unit time

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and bearing resistance, the wheel stiffness, the hand rim size, static stability, the seat position, and the wheel camber.

Bednarczyk and Sanderson<sup>21</sup> showed that adding 5 to 10kg of mass to low-mass MW systems did not change wheeling kinematics, at least when wheeling on level ground, for the low speed and short distances used in their study. They hypothesized that MW propulsion performance may be more appropriately determined by kinetic and metabolic outcome measures than by kinematic measures.

A recent study by Cowan et  $al^{22}$  designed to determine the effect of surface type, MW weight, and axle position on MW propulsion, showed that for novice older adults, MW weight negatively affects kinetic data and self-selected speeds.<sup>22</sup> Nevertheless, using a 3-dimensional accelerometer to measure 3 masses (50, 70, 90kg) in 3 positions corresponding to 3 distributions (10, 40, 70%) of the system's total mass upon the front casters, de Saint Rémy et  $al^{23}$  found that the MW deceleration was explained more by the mass distribution on the front casters (92%) than by the system's total mass (8%).

Based on our bibliographic review, the effect of MW mass alone on efficiency is still unclear. There are few experimental studies that focus on mass<sup>21</sup> for the purpose of establishing the effect of MW mass alone on efficiency. One view is that MW mass has little effect on efficiency when propulsion is on level ground (ie, low kinetic and potential energy variation). Another view is that a MW with a lighter mass is easier to push and, therefore, more energy efficient (ie, low rolling resistance).<sup>18</sup> For certain activities, such as carrying the MW or loading it into (or unloading it from) a car, the MW mass could be, in our opinion, a hindering factor for people with a greater level of physical disability. However, this subject never seems to be examined.

In any case, based on the limited studies available, MW mass seems unlikely to be the sole factor or a main factor accounting for increased efficiency or functionality of 1 MW over another. However, in clinical practice, MW mass is one of the criteria vaunted the most often by vendors and by consumers when purchasing a MW despite the considerable financial consequences. (ie, anecdotally the lightest is the best). For example, a MW covered by the French Health Care System weighs an average of 14kg. Subjects who want to buy a MW that weighs 5kg less than this French Health Care System wheelchair will need to pay 3 to 4 times more.

Because the influence of MW mass remains undetermined and there is little literature on this subject, this study was performed to verify whether mass influences the changes in physiologic responses, perceived exertion, and performance during various simulated daily tasks involving MW displacements. Our hypotheses were as follows: during many daily tasks, additional MW mass above a critical level (to be determined) would produce (1) an increase in all physiologic parameters, (2) an increase in the perceived exertion, and (3) a decrease in performance.

### **METHODS**

#### **Participants**

We recruited SCI volunteers from the Valenciennes community (table 1). They were asymptomatic with respect to cardiovascular disease and impairment, had no upper-limb deformities or abnormalities, and participated to various extents in MW sports. We also recruited AB volunteers with the same mean height and weight from the same community (see table 1). This study was approved by the local ethics committee, and all subjects gave their informed consent before the study began. Our experiments conformed to the Helsinki Declaration.<sup>24</sup>

Table 1: Participants' Characteristics			
Characteristic	SCI (n=8)	AB (n=13)	
Age (y)	33.6±11.7 (19–56)	24.3±4.6 (18–37)	
Weight (kg)	73.9±18.2 (54–104)	72±8.6 (60–90)	
Height (m)	1.8±0.1 (1.6–1.9)	1.8±0.1 (1.6–1.9)	
Time since injury (y)	20±9.9 (3–35)	NA	
Cause of SCI	5 traumas,	NA	
	2 congenital and 1 infection		
Wheelchair	<ol> <li>2 Otto Bock Voyager<sup>e</sup> (9.8kg)</li> <li>1 Küschall K4<sup>a</sup> (9.8kg)</li> <li>2 Quickie Revolution<sup>f</sup> (10.4kg)</li> <li>1 Küschall Champion<sup>a</sup> (11.1kg)</li> <li>2 Quickie Neon<sup>g</sup> (9.7kg)</li> </ol>	Küschall K4 <sup>ª</sup> (9.8kg)	

NOTE. Mean  $\pm$  SD and range of values for age, weight, height, and time since injury.

Abbreviation: NA, not applicable.

#### Instrumentation

*Manual wheelchairs.* The AB group used a standard nonadjustable multisport MW (Invacare Küschall<sup>a</sup>) weighing 9.8kg. The members of the SCI group used their own personalized multisport MW, weighing approximately 10kg (see table 1). A small system for adding mass to the MWs was positioned out of the subject's field of vision, under the seat and next to the rear axle of the MWs (fig 1). This position, near to the MW center of mass, was chosen to minimize the influence of the settings of the wheelchairs (ie, stability and rotational inertia around the vertical axis, important in the trajectory changes, such as slaloms).<sup>23-25</sup>

#### Measurements

Energy expenditure was estimated from the  $\dot{V}O_2$  and the  $CO_2$  production measured with a K4 system.<sup>b</sup> Weighing 1.5kg, this system is a portable unit worn by the subject, including a silicon mask containing a flow-rate turbine placed on the subject's face, a processing unit containing the  $O_2$  and  $CO_2$  analyzers, and a battery pack. The processing unit and the battery pack were placed with the subject on the MW seat. Every day, the turbine was calibrated with a 3-L syringe, and a 2-point calibration of the  $O_2$  and  $CO_2$  analyzers was carried out using ambient air and a standard calibration gas mixture (5% CO<sub>2</sub>, 16%  $O_2$ , 79%  $N_2$ ). The energy expenditure was expressed in milliliters per kilogram of body weight (see "Data Analyses").

Heart rate, expressed in total number of beats (see "Data Analyses"), was recorded using a sport monitoring system (Polar<sup>c</sup>) to indicate the exercise intensity during MW displacements.

Visual analog perceived exertion was estimated on a 20-cm visual analog scale ranging from "no exertion at all" to "maximum exertion." After each mass condition, all subjects were asked to state their perceived exertion rate during propulsion. In addition, they were asked to state which of the 4 possible masses (0, 1, 2, 5kg) they thought was under their MW.

## Tests

Six independent tests were conducted during this study for all mass conditions:

• Test A consisted of executing 15 stop-and-go maneuvers while moving the MW in a straight line at a self-selected comfortable speed. The stop-and-go markers were positioned 5m apart.



Fig 1. The system to add mass to a MW out of the subject's field of vision.

- Test B consisted of propelling the MW for 2 minutes at a self-selected comfortable speed on a treadmill set at a 3% incline.
- Test C was the same as Test B, but with the treadmill set at a 5% incline.
- Test D consisted of crossing 10 sidewalks (1.25m long and .075m high) at a self-selected comfortable speed. The sidewalks were 5m apart.
- Test E consisted of slaloming at a self-selected comfortable speed between 20 markers placed in a straight line. The markers were positioned 1.5m apart.
- Test F consisted of executing a 75-m sprint as fast as possible.

## Procedures

The 6 independent tests were performed to determine the influence of MW mass on physiologic (ie, EE, heart rate), perception (ie, visual analog perceived exertion) and performance responses (ie, time in seconds on test F). Four different masses were added to the individual MWs: 0, 1, 2 and 5kg. All these masses had the same size and form (see fig 1), and the 0kg mass was made of cardboard in order to simulate adding it to the MW. Because the study was a repeated-measures design, the potential mass effect of the K4 equipment (1.5kg) was the same for all MW field measurements.

Before the tests, the equipment was fitted to each subject, and the subject was given 3 to 5 minutes to become familiar with breathing into the mouthpiece and propelling while wearing the apparatus. The self-selected comfortable speed was determined by asking all subjects to move their MW 3 times between preset markers. During the tests, a metronome was used to maintain the self-selected comfortable speed. After a 5-minute rest, baseline resting data for the physiologic parameters were recorded for 2 minutes. The EE and heart rate were recorded for the duration of the trial (eg, test C, mass condition, 2kg), and the visual analog perceived exertion was recorded after each trial. Between mass conditions and tests, as long a time as necessary was permitted to allow a return to basal heart rate. The only advice given to the subjects was to propel their MW and pay attention to the MW dynamics (eg, stability, propulsion, comfort).

Mass conditions (0, 1, 2, 5kg) and tests (A, B, C, D, E) were executed in random order to minimize bias. Test F, considered the most tiring, was executed after the other tests.

## **Data Analyses**

Subjects were compared with themselves and not between groups. This was done because, although the AB group was familiar with MW locomotion, we assumed that they did not have the same level of skill and perception as the SCI group because of a lack of constant practice. Consequently, we feared they would bias our results. However, the AB group could represent novice subjects with SCI and provide supplementary information about practice time.

Based on the number of tests (6) and mass conditions (4), this study was designed to measure submaximal physiologic responses over a short period rather than a steady-state situation. This procedure allowed the mass conditions to be tested exhaustively, although it did not test the population representativeness of the results for all daily tasks. It was thus decided to use the integral of heart rate and  $\dot{V}o_2$ , which quantifies the total number of heartbeats, and the total  $o_2$  consumed to execute a task respectively (ie, the more intense the submaximal task, the more these parameters increase). The integrals were calculated from the first 20 seconds to the end of the tests. This



Fig 2. (A) SCI group and (B) AB group. Means and SDs of the heart rate integrals for all tests. For the 2 groups, no significant difference was found between mass conditions for all tests. Tests: Sidewalk (black), Stop-and-Go (gray), Slalom (white), Treadmill (checkered), Treadmill 5% (stripes).

procedure was employed to account for stable participant propulsion.

Statistical analysis was done using Statistica.<sup>d</sup> The results are expressed as mean  $\pm$  SD. The normality of the distribution and the homogeneity of variances for each dependent variable were tested respectively using a Shapiro-Wilks test and a Levene test. A 1-way analysis of variance for repeated measurements was used to analyze the MW mass in terms of the physiologic responses, perception, and performance. Tukey post hoc tests were performed when significant mass effects existed. This test takes into consideration the correction necessary for our 4 mass conditions; we adopted a statistical significance *P* under .05 for this test.

#### RESULTS

Twenty-one volunteers (8 SCI; 13 AB) (see table 1) participated in the experiments. All subjects completed all tests in all conditions without difficulty.

Increases in heart rate, oxygen volume, and visual analog perceived exertion were noted according to the difficulty of the imposed tasks (figs 2–4). The tasks were varied (eg, test B to test C) in order to accentuate the discrepancies of the parameters in terms of the added mass. Nonetheless, there was no significant effect of mass found for either group (SCI & AB) for all tests, both for the heart rate integral (see fig 2) and for the  $Vo_2$  integral (see fig 3). In addition, for the visual analog perceived exertion, no significant effect of mass was found for the SCI group for any test (see fig 4).

However, for the AB group, the added mass had a significant effect in the visual analog perceived exertion (F=6.11; P=.02) for test A, Stop-and-Go (see fig 4). A post hoc Tukey test showed a significant difference between the 0kg and 5kg mass conditions (P<.01; d=.8), between the 1kg and 5kg mass conditions (P=.02; d=.6), and between the 2kg and 5kg mass conditions (P=.01; d=.6). For both groups, there was also no significant effect of mass found for the performance in test F, Sprint (fig 5).

For all tests, the participants were asked after each mass condition what mass they thought was under their MW seat. For the SCI group, 78.4% answered incorrectly when nothing



Fig 3. (A) SCI group and (B) AB group. Means and SDs of the  $\dot{V}_{0_2}$  integrals for all tests. For the 2 groups, no significant difference was found between mass conditions for all tests. Tests: Sidewalk (black), Stop-and-Go (gray), Slalom (white), Treadmill (checkered), Treadmill 5% (stripes).



Fig 4. (A) SCI group and (B) AB group. Means and SDs of the visual analog perceived exertion for all tests. For the SCI group, no significant difference was found between the mass conditions for all tests. For the AB group, a significant difference was found between the mass conditions for the Stop-and-Go test. Tests: Sidewalk (black), Stop-and-Go (gray), Slalom (white), Treadmill (checkered), Treadmill 5% (stripes), Sprint (taupe). \*Between the 0kg and 5kg conditions (P=.01). \*Between the 1kg and 5kg conditions (P=.02). \*Between the 2kg and 5kg conditions (P=.01).

was added, 62.2% when 1kg was added, 56.7% when 2kg was added, and 81.1% when 5kg was added. For the AB group, 75% answered incorrectly when nothing was added, 78.6% when 1kg was added, 56.7% when 2kg was added, and 57.1% when 5kg was added.

### DISCUSSION

Except for the visual analog perceived exertion of the AB group during the Stop-and-Go test, there were no changes in the EE, heart rate, visual analog perceived exertion, and performance between 0kg, 1kg, 2kg, and 5kg conditions for all groups and all tests. When the participants were asked whether they knew which mass was under their MW seat, they answered correctly around 1 out of 3 times. It is nonetheless surprising that participants could not identify the mass more correctly. We assume that the mass and its inertia translation are masked by other factors, such as bearing quality, chassis rigidity, and the rotational inertia of wheels and tires. From a mechanical perspective, the results are not unreasonable because, in fact, the ratio of the system's mass in movement (ie, subject plus MW plus K4) to the added mass is low (ie, 1 to 6%).

The only significant result was for the AB group, who perceived more exertion in the Stop-and-Go test (see fig 4) when the MW was loaded with 5kg compared with 0kg, 1kg, and 2kg. For the SCI group, no difference was perceived, possibly because 5kg was not an important hindering load for habitual MW users compared with the nonhabitual users in the AB group. Nevertheless, the heart rate or  $\dot{V}o_2$  integrals for the AB are no higher than those of the SCI group.

With an SCI group (N=9), Hilbers and White<sup>18</sup> found differences in EE when comparing at different velocities 2 MWs with different masses and designs: a sport MW weighing 9.8kg and a conventional MW weighing 18.9kg. These authors, like the authors of other studies,<sup>19,23</sup> hypothesized that the mass



Fig 5. SCI and AB groups. Means and SDs for the Sprint tests. For the 2 groups, no significant difference was found between mass conditions. Sprint tests: SCI (gray), AB (white). was not the most important factor because the 2 MWs had the same external work rate and mass was included in this calculation. They attributed the EE variations to other factors (eg, sitting posture; cambered wheels; narrow, highly inflated tires) than the smaller mass of the sport MW compared with the conventional MW. In their study, the work rate was calculated and the metabolic responses were measured based on a constant velocity; they did not consider the effect of inertia and the energy required to set an object in motion (ie, main acceleration, kinetic energy variations). The conventional MW, which has twice the mass of the sport MW, will require more EE to accelerate and decelerate, making the sport MW design even more advantageous if the pattern of activity requires numerous stops and starts.

Unlike the tests of Hilbers and White,<sup>18</sup> 4 of our tests— Sidewalks, Treadmill 5% (main potential energy variation), Stop-and-Go, and Slaloms (main kinetic energy variation) were supposed to enhance the inertia effect, and despite this, the measurement instruments did not detect any modification of EE and heart rate. Quantifying the effect to set the MW in motion and expressing it as a percentage of the total work executed would perhaps be pertinent. From a mechanical perspective, such results would complement our physiologic measurements, helping to demonstrate that up to weights of 5kg, the mass is negligible.

Several studies have compared the effect of different MWs. However, these studies change MW mass together with other parameters (ie, design, settings), thus preventing drawing conclusions about the effect of mass alone.<sup>18,19,21,26</sup> For our study, the SCI group propelled their personalized MWs, and the AB group propelled the same MW. The different masses were placed under the MW seat out of the subject's field of vision. The MW velocity during the field tests was controlled by a metronome, insuring that the variations in velocity occurring from condition to condition were small (ie, difference of  $\pm 2s$ to execute the same test in different conditions). For these reasons, this study could contribute greatly to the knowledge about the effect of mass alone. The method used in this study seems appropriate, although the results could be improved by increasing the range of mass added and adding other biomechanical evaluation parameters.

## **Study Limitations**

The main limitation of this study is the relatively small sample size (SCI, n=8; AB, n=13). With a small sample size, the danger is a type 2 error. The power size test calculated from our main outcomes for SCI and AB groups showed high values (ie, .77 to .92) for the AB group total  $\dot{V}o_2$  during the Stopand-Go test, the SCI group total heart rate during Treadmill 5% test, and the AB group total heart rate during Sidewalk test. For the others, 22% of the power size tests were between .3 and .7, with the last tests less than .3. In order to confirm our results, it would be necessary to have a greater population size systematically to have a power greater than or equal to 0.8. Finally, although the participants have more or less performed all the conditions in the same time (ie, ±2s), it is difficult in field measurements to control more precisely the speed in short intervals without adding supplemental constraints.

## CONCLUSIONS

These preliminary findings suggest that loading a multisport MW with additional mass (up to 5kg) does not seem to have an effect—or at least, no more than a minor effect—on the physiologic responses, the perceived exertion, and the performance outcomes for many of the daily activities performed in this study. Further long-term investigations should be performed to corroborate our results and could help manufacturers improve MW design and settings rather than reduce MW weight by using expensive materials. Such studies could also help vendors guide subjects toward more suitable MW choices.

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#### **Suppliers**

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- b. COSMED S.r.l., Via dei Piani di Monte Savello 37, PO Box 3, 00040 Pavona di Albano, Rome, Italy.
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