Quantifying the Effects of On-the-Fly Changes of Seating Configuration on the Stability of a Manual Wheelchair

Louise Thomas, *Student Member, EMBS,* Dr. Jaimie Borisoff, and Dr. Carolyn J. Sparrey

Abstract— **In general, manual wheelchairs are designed with a fixed frame, which is not optimal for every situation. Adjustable on the fly seating allow users to rapidly adapt their wheelchair configuration to suit different tasks. These changes move the center of gravity (CoG) of the system, altering the wheelchair stability and maneuverability. To assess these changes, a computer simulation of a manual wheelchair was created with adjustable seat, backrest, rear axle position and user position, and validated with experimental testing. The stability of the wheelchair was most affected by the position of the rear axle, but adjustments to the backrest and seat angles also result in stability improvements that could be used when wheeling in the community. These findings describe the most influential parameters for wheelchair stability and maneuverability, as well as provide quantitative guidelines for the use of manual wheelchairs with on the fly adjustable seats.**

I. BACKGROUND

The majority of manual wheelchairs have a fixed frame, which does not allow for spontaneous changes in configuration after the initial setup [1]. However, user-initiated changes to seating (e.g. power wheelchairs with seat elevators, Elevation™ manual wheelchair) can help accomplish mobility related activities of daily living, such as transfers, participating in social activities, and extending reach [2]. These on the fly or dynamic seating adjustments allow users to change their wheelchair seat configuration throughout the day to better suit different activities [3].

Changes to seating shifts the center of gravity (CoG) of the system, potentially influencing wheelchair stability (defined as the tip angle of the wheelchair) and ease of wheeling (i.e. maneuverability). Stability and maneuverability are individually improved by shifting the system CoG in opposing directions [1], [4]. A trade-off is generally made between the two performance metrics, with the configuration of a typical fixed-frame wheelchair usually optimized for level ground wheeling. However, this is sub-optimal for situations such as traveling up or down slopes. Dynamic seating adjustments can lessen these compromises and improve task specific stability and maneuverability.

The backrest position, in particular, was identified as important and a target for on the fly adjustability to improve wheelchair use [3], [7], although its effects have not been fully studied. Other parameters may also be important, yet few studies have taken a holistic approach to examining multiple wheelchair configuration parameters at once.

II. PURPOSE

The aim of this study was to quantify the effects of seat angle, backrest angle, user position (i.e. "offset" between a user's hips and the backrest), user mass, and rear axle position (*Figure 1*) on the stability and maneuverability of an ultralight manual wheelchair. Maneuverability was defined by the front/rear weight distribution of the wheelchair system, where a greater percentage of weight on the rear wheels indicated the wheelchair was easier to push but less stable. A result of 100% signified a backwards tip, and 0% a forwards tip. The resulting equations enabled us to study the relationships between each of the six variables, including the relative effect of the ground slope angle.

III. METHODS

Wheelchair stability and maneuverability were evaluated using rigid body dynamic simulation (MADYMO TASS International, Netherlands). A range of ISO test dummies (25kg to 125kg, with increments of 25kg) represented the wheelchair user.

A. Wheelchair model development

The simulation was created using a CAD model of an ultralight manual wheelchair with dynamic seating (early

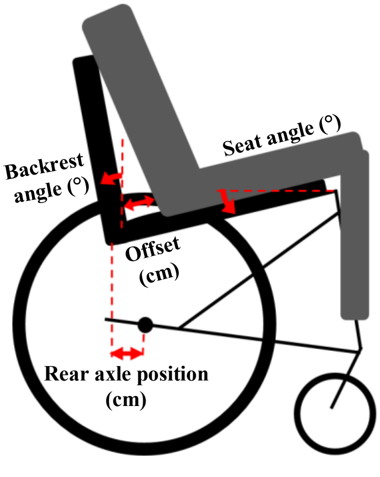

Figure 1: Wheelchair configuration changes used in simulation.

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L. Thomas and C. Sparrey are with the Mechatronic Systems Engineering Department, Simon Fraser University, Surrey, BC, Canada (phone: 778-868-9015; e-mails: lthomas@sfu.ca and csparrey@sfu.ca).

J. Borisoff is with the British Columbia Institute of Technology, Burnaby, BC, Canada (email: jaimie_borisoff@bcit.ca).

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model Elevation, PDG Mobility, Vancouver, BC). The wheelchair had 24” diameter wheels, 5” casters, a seat depth of 16”, and a seat width of 16”. The frame, including the seat and backrest, was 7.62kg (Table I), with center of gravity (CoG) positioned 20cm behind the front axles and 37.3cm above the ground. The rear wheels were 1.80kg each, and the casters 0.38kg. Each wheel CoG was positioned at the axle.

TABLE I. WHEELCHAIR MASS AND INERTIA

	Mass (kg)	*I_{xx}, I_{yy}, I_{zz}, I_{xy}, I_{yz}, I_{xz} (kg.m^2)*
Front wheels (x2)	0.38	[0.0005, 0.0009, 0.0005, 0, 0, 0]
Rear wheels (x2)	1.80	[0.067 0.132 0.067 0.002 0, 0, 0]
Wheelchair frame	7.62	[0.206, 0.228, 0.336, 0, 0, -0.075]

B. *Experimental model validation*

The wheelchair mass and horizontal position of the CoG were validated using scales under each of the four wheels. The vertical position of the CoG was calculated from the tipping point of wheelchair.

A 113kg test dummy was used for validation. The mass of the torso was 62.87kg, thigh 41.57kg, and each leg 4.11kg. The CoG of each component (Table II) was calculated using a pivot and scale, with measurements taken from the outermost point of the dummy hip when in a seated position.

TABLE II. DUMMY MASS COG

	Horizontal CoG (cm)	*Vertical CoG (cm)*
Torso	11.9	33.6
Thigh	33.1	6.0
Legs (x2)	32.9	-20.4

The full dynamic model of the wheelchair was validated by comparing the stability of the simulation to that of the physical wheelchair. Static stability tests (Figure *2*), as defined in ISO 7176.1, compared the angles at which the wheelchair tipped over for different configurations.

A 3D motion capture system (Qualisys, Sweden) was used to determine when the uphill wheels started lifting off and the angle of the ramp. The wheelchair marker set was comprised of 26 markers, with those in Figure 3 mirrored on the opposite side. Additional markers were placed on the ramp and ground to determine reference planes.

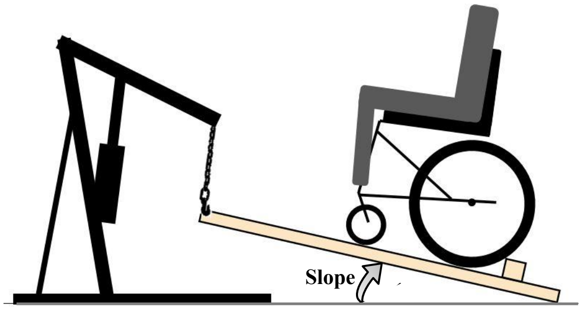

Figure 2. Static stability test setup, showing ramp lifted into a slope with engine hoist and wheelchair stopped from rolling with a block.

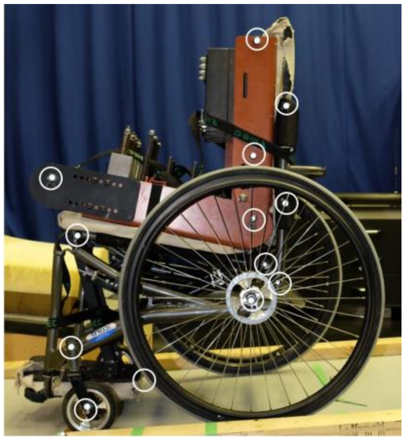

Figure 3. Placement of reflective markers for 3D motion capture. Arrangement mirrored on opposite side to give a total of 26 markers.

C. *Analysis*

The validated simulation was run for a full factorial matrix to determine the effects of each parameter on backwards and forwards stability. Parameter ranges were: the angle of the backrest (-10° to 35°, increments of 15°), seat angle (-10° to 20°, increments of 10°), rear axle position (0cm to 20cm, increments of 5cm), offset distance between the user and the backrest (0cm to 6cm, increments of 1cm), and user mass (25kg to 125kg, increments of 25kg). The users were represented by standard ISO wheelchair dummies.

Nonlinear step-wise least squares regression analyses (JMP v 12 SAS) were performed for backwards stability and the front/rear weight distribution on various slopes. Second order models were developed including interaction effects. Terms with p-values < 0.0001 were considered significant.

IV. RESULTS

A. *Experimental testing*

The simulation was validated experimentally for 3 different seat and backrest angles (*Figure 4)*. The root-mean-square error (RMSE) between the simulation and experiment was 1.21° for backwards stability, and 2.05° for forwards stability.

B. *Regression analysis*

For the range of values explored in the simulations, the rear axle position had the greatest effect on wheelchair stability (Eq.1, Figure 5). The backrest angle and rear axle position were inversely related to the backward tip angle. The user offset had a linear effect on stability, and the wheelchair was more stable for heavier users:

$$\text{Backward tip angle} = 38.89 + 0.0824 \cdot S - (0.00531 \cdot S + 0.00092 \cdot M + 0.407)B - 1.14 \cdot R + 0.536 \cdot U + (0.00127 \cdot M + 0.191)M \tag{1}$$

where B is the backrest angle in degrees, S is the seat angle (degrees), R is the rear axle position (cm), U is the user offset (cm), and M is the user mass (kg). The equation correlation coefficient is $R^2 = 0.953$, and the RMSE is 1.27°.

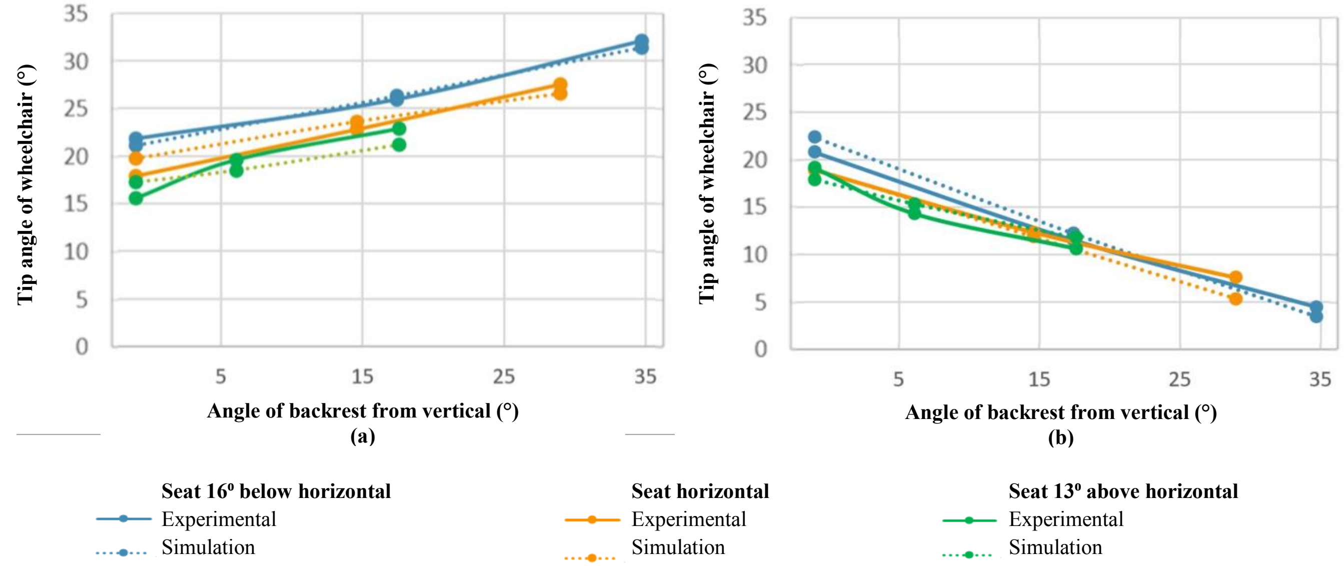

Figure 4. Experimental and simulation derived tip angles showed excellent agreement for all tested wheelchair configurations for both forwards (a) and backwards (b) tips. Tip angle errors were greatest when the backrest was in its most upright position.

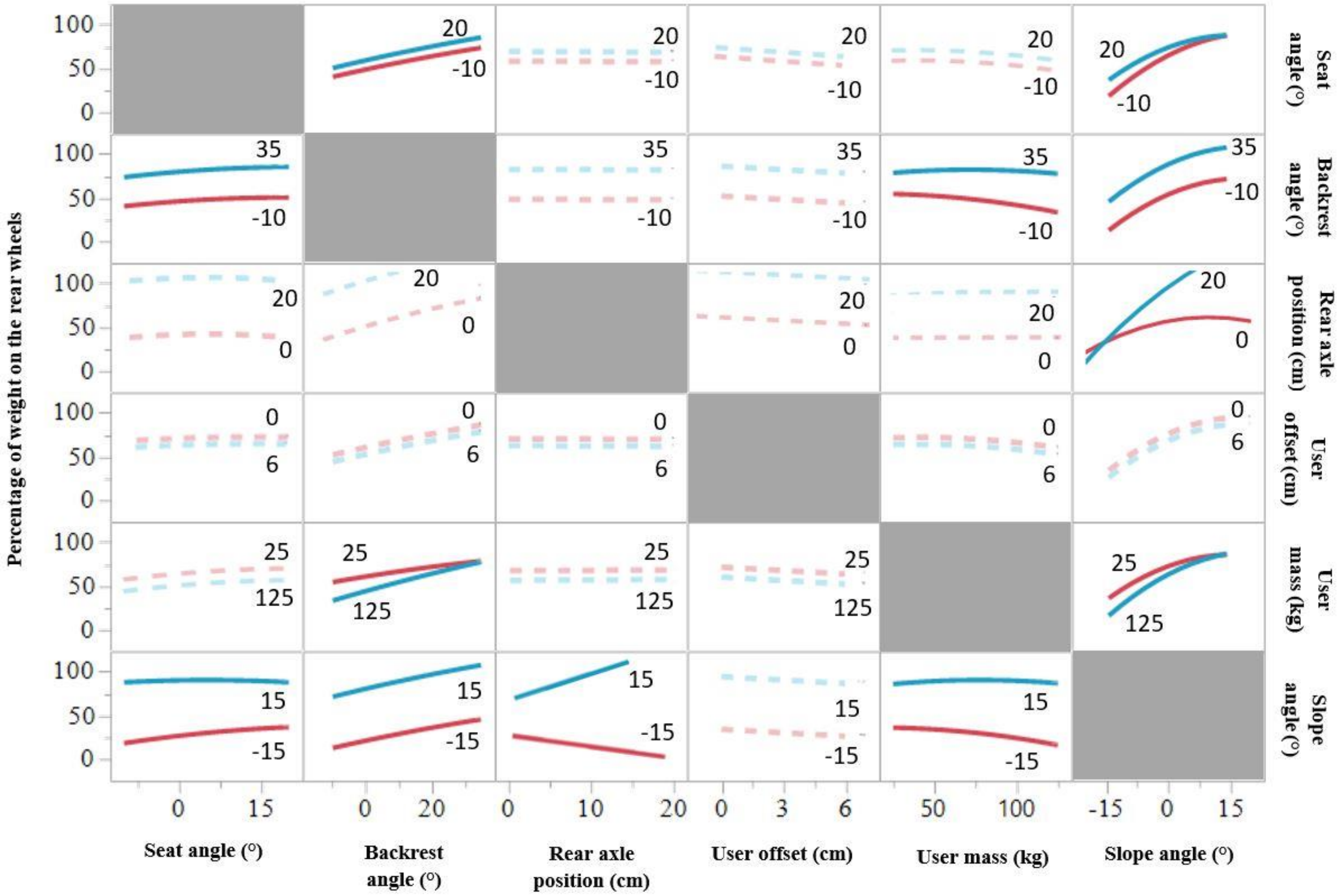

Figure 5. Interaction plots show slope angle affected the impact of most of the wheelchair configuration parameters except user offset on maneuverability. The effects of rear axle position and user offset on maneuverability was consistent throughout the trials. Values for each parameter ranged from seat angle (-10° to 20°), backrest angle (-5° to 35°), rear axle position (0cm to 20cm), user offset (0cm to 6cm), user mass (25kg to 125kg), and slope (-15° to 15°). Each panel shows the effect of the x-axis parameter on the rear wheel load ratio, with colored lines indicating the upper (blue) and lower (red) limits of the row parameters. The difference in slope between the blue and red lines indicates the interaction between the row and column variables, and parameter combinations with no interaction effects are shown by the faded, dotted lines.

The distribution of ground reaction force between the front and rear wheels was calculated as a metric of wheelchair stability and maneuverability. The slope of the ground was the greatest factor for determining the front/rear distribution of the weight, and had significant interaction effects with each of the other parameters apart from user offset (*Eq. 2, Figure 5)*. There were also interaction effects for the backrest angle × seat angle and backrest × user mass.

$$\text{Rear wheel load (\%)} = 40.4 + 0.302 \cdot S + (0.00438 \cdot M + 0.420)B + 2.51 \cdot R - 1.29 \cdot U + (-0.00160 \cdot M + 0.0932)M + (-0.0568 \cdot G - 0.0211 \cdot S + 0.00705 \cdot M + 0.0942 \cdot R + 0.711)G \quad (2)$$

where G is the slope of the ground in degrees. The equation correlation is $R^2 = 0.938$ and RMSE = 5.40%

V. DISCUSSION

The stability and maneuverability of a wheelchair are dependent on a number of parameters, with some fixed during use (e.g. the position of the rear axles, and user mass), some situational or environmental (e.g. the ground slope angle), and some potentially adjustable by the user (e.g. the seat angle, backrest angle, and user offset). Adjustable parameters enable the wheelchair to adapt to situational variables.

A wheelchair should be stable enough to avoid tipping, but more stability than necessary reduces the performance and maneuverability of the wheelchair [4]. The rear axle position is an important parameter for optimizing initial wheelchair configuration. The wheelchair becomes less stable but more maneuverable as the rear axles are moved forward. On level ground, each 1cm shift forward of the rear axle increases the load on the rear wheels by 2.51% of the total system weight. On standard uphill 1:12 ramps (4.8° slope), the effect increases to 2.96% of the system weight. These changes equate to a 1.14° difference in rear stability for each 1cm change in rear axle position.

The user mass is positively related to the backward tip angle of the wheelchair, such that heavier users are more stable. Assuming body proportions similar to ISO wheelchair test dummies, each 10 kg increase in user mass approximately corresponds to a 3 to 4.5° increase in stability. The user mass also increases the effect of changing the backrest angle. Consequently, lighter users with adjustable backrests would need a greater angular adjustment to produce the same stability and maneuverability changes.

Dynamic seating changes, to the backrest in particular, are thought to enable the wheelchair to be more maneuverable on level ground, while also retaining the required stability for wheeling on slopes [3], [7]. The results presented here confirm those assessments. For each degree change in backrest angle, the front/rear weight distribution changes by 0.86% of the system weight for heavier (100 kg) users, or 0.64% for lighter (50 kg) users. For uphill wheeling, rear stability can be increased by adjusting the backrest forward, with each degree backrest change corresponding to a 0.38-0.63° increase in stability. Therefore, for a backrest with 30° of adjustability, stability changes of up to 18.9° can occur. For traveling downhill, a reclined backrest would provide the user with balanced trunk support and negate the need for the user to perform a wheelie.

Changes to the seat height (by changing the seat angle) also have significant effects on stability and maneuverability. On level ground, each degree of seat depression increased the load on the rear wheels by 0.302% of the system. These changes can be used to negate the effects of user movements; for example, if the user changes their position 2 cm forward the same weight distribution can be maintained by lowering the seat by 5°. The effects of seat changes were more pronounced on downhill slopes, and had less of an effect when wheeling uphill.

VI. CONCLUSION

Simulated models for an ultralight manual wheelchair showed that the rear axle position and angle of the backrest were the most influential terms for wheelchair stability and maneuverability. Stability increases of up to 1.14° can be gained for each 1cm shift backwards of the rear axle, and up to 0.63° of stability can be gained by shifting the backrest 1° forward. The axle position should be configured to enable maximal maneuverability without tipping, and dynamic seating changes, particularly to the backrest, can therefore be used to increase task specific stability.

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