Effects of Rear-Wheel Camber on Wheelchair Stability

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Objectives: To evaluate how using a wheelchair with rear-wheel camber (when the bottoms of the wheels are farther apart than the tops) is associated with the risk of instability incidents, and to determine the effect of camber on wheelchair stability.

Design, Setting, Patients: Epidemiologic data were analyzed from a sample of 576 users of manually propelled wheelchairs in Nova Scotia. A controlled trial was performed using a representative wheelchair occupied by an anthropomorphic test dummy, altering the camber in 5° increments from -13° to +15°.

Main Outcome Measures: For the epidemiologic study, univariate and multivariate analyses were used. To measure the static stability, a tilting platform was used according to the guidelines of the International Organization for Standardization. 

Results: Camber users reported significantly more instability incidents; of these incidents, more were in the rear direction (40% vs 27%) and fewer in the lateral direction (17% vs 28%) (p < .01). When controlling for other factors, camber was associated with a 3.91-fold increased risk of sustaining an instability incident (p < .001). With increases in camber angle in the laboratory, lateral and forward stability increased and rear stability decreased (with the wheels unlocked and locked) (p < .001).

Conclusion: Camber use is negatively associated with instability incidents in the lateral direction and positively associated with incidents in the backward direction, probably due in part to the effects of camber on lateral and rear stability.

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A COMMON FEATURE of lightweight, manually propelled wheelchairs is that the user can adjust the camber of the rear wheels. Camber is defined as a position in which the bottoms of the rear wheels are farther apart than the tops of the wheels.1 Camber is known or postulated to affect variables such as kinematic and metabolic efficiency (due to the abducted arm position),2-4 hand protection (eg, when passing through doors),5 rolling resistance,6 the wheelchair's downhill-turning moment on lateral slopes,7 the life of the rear-wheel ball bearings,7 the toe angle of the rear wheel,8 the caster-inclination angle6 and the caster-trail distance.9

Although the effects of camber on stability have never been reported, uncompensated camber also affects several variables that might be expected to affect stability:7 the height of the rear-wheel axle, the base width, the base length, the fore-aft location of the center of gravity (CG), the vertical displacement and tilt angle of the wheelchair frame. Some adverse effects of camber can be compensated for by adjustments to the wheelchair.1

Wheelchair-related injuries due to instability are a major clinical concern.2 The first objective of this study was to evaluate epidemiological data to determine whether there is an association between camber and instability incidents. Our second objective was to determine the extent to which camber affects static stability in the lateral, forward, and rear directions.

METHOD

Epidemiology

For the epidemiologic analysis, we used data previously collected by postal questionnaire in a survey of wheelchair-related instability incidents.2 We assumed that the 576 wheelchair users in this database were representative of the general population of noninstitutionalized users of manually propelled wheelchairs, given that the province of Nova Scotia is composed of both rural and urban populations, has a demographic distribution similar to that of the rest of Canada,10 and provides good access to rehabilitation services.

Wheelchair users were categorized into two groups on the basis of the presence or absence of rear-wheel camber. The two groups were compared with respect to the number of instability incidents (complete tipover and/or fall from the wheelchair), the direction of the instability incidents (forward, lateral, or backward), the circumstances of their occurrence, whether an injury resulted, the severity of injuries sustained, and other characteristics (eg, age, body-mass index, gender, how long the person had been using the wheelchair, the time spent using the chair during the day, and the reason the person was using a wheelchair).

We used Chi-square tests for comparisons of two proportions (eg, gender) and two-sample t tests for comparisons of means for the continuous variables (eg, age). The significance level was set at p < .05. We assumed a normal distribution of the data, considering the large sample size and the content validity of the questionnaire items.8 Correction for multiple comparisons (Bonferroni) were made.

Using the 374 questionnaires that were complete enough, we also performed a multivariate analysis to determine if camber was independently associated with an increased risk of instability incidents. Logistic regression models were developed by means of a manual backwards-selection process, we removed variables from the model, one by one, if they did not contribute to the model as judged by the difference in deviances, repeating the procedure until only those variables that contributed significantly to the model remained. The independent strength of association (Odds Ratio [OR]) and the statistical significance (p value and confidence interval [CI]) of the variables were reported for this final model. We performed the analysis using
the PROC LOGIST program in the statistical computer package STATA.4

Static Stability

We selected a foldable, lightweight wheelchair9 with "mag" rear wheels and solid rubber tires. This wheelchair was representative of the way that most lightweight wheelchairs permit camber to be adjusted, namely through an axle plate that could be incrementally tilted with respect to the frame. Some of the newer wheelchairs have pre-set inserts for the axle tubes that compensate for some of the effects of camber (eg, toe out but not axle height). We chose to isolate camber as the only parameter varied rather than contaminate the results by partial compensation.

We built camber-adjustment plates similar to those originally supplied by the manufacturer except that they allowed us to test camber settings between -15° and +15° at 5° increments. (The range of positive camber values reflects what is found clinically; we tested the negative camber, which is not used clinically, to extend the range of measurement and to make the study more complete.) We did not rely on the reading on the camber plate but measured camber with a precision square according to the ISO recommendations.11

The wheelchair was occupied by an anthropomorphic test dummy (ATD),9 a 95th-percentile male (96.0kg), that was tightly bound to the wheelchair. That stability is affected by the characteristics of the wheelchair occupant is well established in the literature.12,13,14 In this study, we chose to eliminate this source of variability by the use of an ATD. The ISO standard on the determination of static stability11 requires that an ATD be used for this reason. The characteristics of the ATD that we used are based on the anthropomorphic data of Dempster and Gaughran,15 the standard reference in biomechanical and engineering studies.

Static stability was measured using the ISO guidelines,11 the reliabilities of which have been previously established.12,13,14,16 Although static stability is only one determinant of dynamic stability (where acceleration and deceleration also become important), the correlation is good between static and dynamic stability,13,15 and there are no internationally accepted methods for the determination of the dynamic stability of manual wheelchairs.

We tested static stability in the lateral, forward, and rear directions. For each direction of stability, the wheelchair was placed on a test platform with the axis of rotation of the wheelchair parallel to the platform axis of rotation. Then the platform was slowly tilted until the uphill wheels became unweighted. When this happened, we used an electronic inclinometer9 to measure the angle of the platform from the horizontal, to the nearest 0.1° (the tipping angle). For lateral stability, we looked at one side only, assuming that there would be no clinically significant difference between the right and left lateral stabilities.17 Rear stability was determined with the brakes locked and unlocked.

We found the best-fitting curves relating the camber and stability values, using the least-sum-of-squares method and regression/correlation analysis. We compared the rear stability with the brakes locked and unlocked, using a matched-pairs t test.

RESULTS

Epidemiology

Camber users constituted 21% (120 of 576) of the sample. The proportion of subjects reporting wheelchair-instability incidents was much greater among camber users (83%) than among nonusers (50%) (p < .001). Camber users reported having significantly fewer lateral-instability incidents (17% vs 28%, p < .01) and more rear-instability incidents (40% vs 27%, p < .01) than nonusers (fig 1). The location of these incidents was also dissimilar in the two groups. Of the 432 who responded to this question, camber users were significantly more likely to have had instability incidents while playing basketball (p < .001). There was no difference between the two groups concerning the number of incidents occurring outside, inside, on a ramp, at a doorway threshold, sidewalk curbcut, or during transfer to a van.

The percentage of subjects reporting injuries due to instability incidents was also higher among camber users than among nonusers (42% vs 28%, p < .01). However, in the subset of subjects who had reported instability incidents (100 of the 120 camber users, 230 of the 456 nonusers), 49% of camber users and 53% of nonusers had sustained an injury (p = .45) and 11% experienced serious injuries in each group (p = .66). Camber users differed from nonusers in a number of other ways (table 1): they were significantly younger, more likely to be male, more likely to have used a wheelchair for a shorter period of time, more likely to use their wheelchairs daily, and more likely to have paraplegia (or tetraplegia) than multiple sclerosis and cerebral palsy as the reason for wheelchair use.

In the multivariate analysis, we found camber, adjusted for other variables included in the model, to be an independent risk factor for instability incidents (table 2), but not injuries. Because camber users constituted a younger group, we also stratified the persons who had instability incidents into two equal groups by age. When we ran a model in the group of subjects under 43 years (the younger half of the database), camber came out still more strongly as a risk factor for instability incidents (OR: 5.84, p < .001, 95% CI: 2.02-16.87).

Fig 1. Direction of instability incidents. Each person could report up to 3 instability incidents. A total of 104 camber users reported 149 instability incidents and 271 nonusers reported 333 incidents. The percentages shown are of the incidents (p < .01).
Static Stability

As the camber of the wheelchair's rear wheels increased from \(-15^\circ\) to \(+15^\circ\), lateral and forward stability increased, whereas rear stability decreased, both when the brakes were locked and when the brakes were unlocked (fig 2). The range of lateral-stability values (\(13^\circ\) to \(27^\circ\)) was greater than the ranges of values for forward stability (\(23^\circ\) to \(30^\circ\)) or for rear stability (\(10^\circ\) to \(16^\circ\) with the brakes unlocked and \(6^\circ\) to \(9^\circ\) with the brakes locked). The values for rear stability with the brakes locked were consistently lower than with the brakes unlocked (mean difference 5.6°; SEM 0.3°, \(p < .001\)).

The regression equations that expressed the relationship between camber and stability values were all highly significant (table 3). The equations for lateral and rear stabilities were linear but the equation that best described the experimental data for forward stability was quadratic. This implies that the wheelchair would be least stable at \(-10.5^\circ\) of camber (22.6° of stability) and the stability would increase below and above this value.

**DISCUSSION**

Our objectives, to determine whether there was an association between camber use and instability incidents and to determine the effects of camber on wheelchair stability, were met. Epidemiological analyses showed that subjects who used wheelchairs that had cambered rear wheels constituted a rather homogeneous group that was different from other noninstitutionalized users of manually propelled wheelchairs. Importantly, they sustained more instability incidents and more injuries. The multivariate analysis indicated that camber users had a 3.91-fold increased risk of having an instability incident. The Odds Ratio rose to 5.84 in the subjects who were 43 years of age or younger. The difference in the direction of instability incidents was of particular interest; a significantly smaller proportion of camber users had their instability incidents in the lateral direction and a higher proportion in the rear direction. Our multivariate analysis also identified and quantified other risk factors for wheelchair instability incidents (table 2) that complement a previous report, but which are incidental to the object of this study.

The increase in lateral and forward stabilities and the decrease in rear stability with negative camber that we found in the laboratory are consistent with, and provide concurrent validation of, the epidemiological data. The changes in stability values, expressed as a percentage change from the value associated with the most camber, were +106% for lateral stability, +31% for forward stability, and -39% and -31% for rear stability with the wheels locked and unlocked, respectively. The percentage changes within the usual clinical range of camber variation (0° to 15°) were about half as large. The absolute rear-stability values were smaller than those for lateral or forward stability.

**Table 1: Characteristics of Wheelchair Users**

<table>
<thead>
<tr>
<th>Variables</th>
<th>With Camber</th>
<th>Without Camber</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yr)</td>
<td>33.8 (SD, 15.8)</td>
<td>46.9 (SD, 22.0)</td>
</tr>
<tr>
<td>Body Mass Index</td>
<td>23.9 (SD, 4.4)</td>
<td>24.0 (SD, 5.9)</td>
</tr>
<tr>
<td>Gender (% male)</td>
<td>76</td>
<td>52</td>
</tr>
<tr>
<td>Time (yr) using a wheelchair</td>
<td>9.5 (SD, 7.0)</td>
<td>11.4 (SD, 10.2)</td>
</tr>
<tr>
<td>Uses wheelchair daily</td>
<td>111 (92%)</td>
<td>357 (78%)</td>
</tr>
</tbody>
</table>

Abbreviation: SD, standard deviation.

* Significant at \(p < .01\).
† Significant at \(p < .001\).

**Table 2: Multivariate Analysis of Camber as a Risk Factor for Instability Incidents**

<table>
<thead>
<tr>
<th>Variables</th>
<th>Adjusted Odds Ratios</th>
<th>95% Confidence Interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Having an amputation</td>
<td>4.311</td>
<td>1.52-12.19</td>
</tr>
<tr>
<td>Camber</td>
<td>3.911</td>
<td>1.94-7.87</td>
</tr>
<tr>
<td>Use for recreation/sport</td>
<td>2.631</td>
<td>1.51-4.65</td>
</tr>
<tr>
<td>Use of a knapsack</td>
<td>1.52*</td>
<td>1.10-2.10</td>
</tr>
<tr>
<td>Time using a wheelchair</td>
<td>1.061</td>
<td>1.03-1.10</td>
</tr>
<tr>
<td>Female gender</td>
<td>.47*</td>
<td>.28-.78</td>
</tr>
</tbody>
</table>

* Significant at \(p < .01\).
† Significant at \(p < .001\).

**Table 3: Regression Equations Relating Stability and Camber Angles**

<table>
<thead>
<tr>
<th>Direction</th>
<th>Regression Equation</th>
<th>(P) Value</th>
<th>(R^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lateral</td>
<td>(y = .427x + 19.2)</td>
<td>&lt;.001</td>
<td>95.7%</td>
</tr>
<tr>
<td>Forward</td>
<td>(y = -.0065x - .18x + 23.5)</td>
<td>&lt;.001</td>
<td>98.0%</td>
</tr>
<tr>
<td>Rear</td>
<td>(y = .175x + 14.1)</td>
<td>&lt;.001</td>
<td>90.3%</td>
</tr>
<tr>
<td>Brake unlocked</td>
<td>(y = -.114x + 8.3)</td>
<td>&lt;.001</td>
<td>95.8%</td>
</tr>
</tbody>
</table>

In equations, \(y\) is the stability angle, \(x\) is the camber angle, in degrees.
When one adds other factors that decrease stability (eg, leaning and reaching backward) to rear stability that is already low, the margin of safety is further diminished. The nearly twofold difference in rear stability that we found between the brakes-locked and unlocked situations is consistent with other reports.17,18

The changes in static stability that we found in the laboratory can probably be explained by a combination of uncompensated mechanical effects of camber on the wheelchair.4 For any wheelchair user who appears to be at high risk of instability incidents, compensatory changes to the wheelchair should be considered to restore optimal stability.8,13-14,16-17 Examples of such changes include moving the wheelchair frame forward on the rear-wheel axle17 or positioning equipment or loads closer to the front.19 Prescription of appropriate antitipping devices also can act preventatively. Targeting this group for appropriate intervention to prevent instability incidents.

Although much remains to be learned about the impact of camber variation on performance and safety, no previous study of the effects of rear-wheel camber on wheelchair stability has been published. We found strong epidemiological and experimental evidence of an association between camber and stability. Camber use is negatively associated with instability incidents.72-37-46. For any wheelchair user who appears to be at high risk of instability incidents, compensatory changes to the wheelchair should be considered to restore optimal stability.8,13-14,16-17 Examples of such changes include moving the wheelchair frame forward on the rear-wheel axle17 or positioning equipment or loads closer to the front.19 Prescripción of appropriate antitipping devices also can act preventatively. Targeting this group for appropriate intervention to prevent instability incidents.

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References

Suppliers
a. STATA statistical computer package: Computing Resource Center, 1040 Fifth Street, Santa Monica, CA 90401.
b. Ultrasound Premier, model no XA6-X770-XRED-X08175PB-X26W-X098-XLTW-XH-X04-X05PLC-X3CUSHION; Everest & Jennings Canada Ltd., 11 Snidercroft Road, Concord, Ontario L4K 2J8, Canada.

c. Hybrid II anthropomorphic test dummy; Alderson Research Laboratories Incorporated, 390 Ludlow Street, PO Box 1271, Stamford, CT 06904.
d. SMARTLIVE digital inclinometer; Wedge Innovations, 552 Mercury Drive, Sunnyvale, CA 94086.