Preventing occupied wheelchairs from falling down stairs

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Abstract—The hypothesis was tested that wheelchairs could be prevented from accidentally falling down stairs. A rigid post was attached to the wheelchair frame immediately behind the caster (clearance of 13 mm) such that it would strike the floor just after the casters dropped off an edge. The device was tested by means of a 3-degree ramp at the lower end of which was a level surface that ended with a 11-cm vertical drop. Twenty able-bodied subjects descended the ramp, by gravity alone, from progressively greater distances up the ramp, to determine the threshold at which the speed of the occupied wheelchair (with and without the device in place) was sufficient to induce a forward tip down the step. Forward tips occurred at a mean (± 1 SD) threshold speed of 0.77 (± 0.06) m/s with the device and at 0.38 (± 0.04) m/s without it, a mean difference of 0.39 (± 0.07) m/s ($p < 0.0005$). This preliminary study suggests that such a wheelchair feature might improve the safety of wheelchairs in conditions involving inadvertent loss of caster support, as when they drop off a stair or ledge.

Key words: accidents, protective devices, wheelchairs, engineering.

INTRODUCTION

Data from the U.S. Consumer Product Safety Commission reveal that a number of wheelchair users have died when their wheelchairs have acciden-

tally fallen down a flight of stairs, or dropped off the side of a ramp (4). Presumably, an even greater number of nonfatal injuries have occurred in similar circumstances. The purpose of this study was to design and test a prototype device to prevent this type of wheelchair accident.

Pilot testing suggested that forward-tipping accidents on curbs (**Figure 1**) or stairs (**Figure 2**) were initiated when the wheelchair casters dropped from the top stair to the next or from the curb to the street, allowing the force line from the center of mass of the wheelchair-occupant combination to fall forward of the caster axles. Although in our pilot work we found that wheelchair footrests or forward stabilizers could limit the extent of tip when the casters dropped off a curb, their forward position limits their effectiveness on stairs.

Reasoning that projections from the wheelchair frame to a position just above the floor and immediately behind the casters could limit the initial drop of the casters and hence the extent of instability, a prototype was built. In this study the hypothesis tested was that such a device reduces the likelihood of full-forward tipping when the casters of occupied wheelchairs drop off a stair.

METHODS

Subjects

Twenty young able-bodied subjects (10 men, 10 women) were studied with their informed consent.

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Figure 1.

Sequence of events as the casters of an occupied wheelchair (without footrests) drop off a simulated curb. In (B) the wheelchair is rotating forward around the rear wheel axles before the casters strike the floor. After that, in (C), the chair continues to rotate forward around the caster axles, until the casters swivel and collapse (D,E,F).

Their mean (± 1 SD) height and weight was 172.1 (± 8.1) cm and 67.5 (± 12.1) kg.

Wheelchair

The wheelchair was a standard commercial folding model (Model # P8AU260-770, Everest & Jennings). The solid front casters were 20 cm and the pneumatic rear tires were 60 cm in diameter. The chair was equipped with swinging detachable footrests and desk-length armrests, and weighed 22 kg.

Stair-safety device

The prototype device used in the study weighed 1.3 kg (for a set of two). Each device consisted of an aluminum base attached to the wheelchair and a removable steel head (shaped like a chisel) to stop forward movement of the wheelchair when engaged. The device was adjustable in the vertical and the anterior-posterior planes and the angle of incidence for the contact surface was easily manipulated. We attached a pair of these devices to the lower frame of the wheelchair behind the casters (**Figure 3**). In this position, the device did not interfere with folding the wheelchair. To approximate conditions

in residential and institutional settings—where the U.S. Consumer Product Safety Commission data indicate that most such accidents occur (4)—we set the clearance between the device and the floor at 13 mm to clear doorway thresholds (1).

Dynamic-stability testing

To generate reproducible speeds for the dynamic testing of the stair-safety device, we constructed a 2.5-m-long plywood ramp on the surface of which 5 cm intervals were marked, beginning at the lower end. At the base of the ramp was a level, 1.53-m-long by 1.22-m-wide plywood platform that was 11 cm above the floor, providing a vertical drop to simulate a stair (2). We used only a single stair for subject safety.

To help determine the ramp angle, we conducted a retrospective study of 62 patients in a rehabilitation setting propelling their wheelchairs on the level; their mean speed was 0.62 (± 0.43) m/s. We then calculated the theoretical speeds at the foot of the ramp with the following formula (ignoring rolling resistance):

$$TS = (19.6 \times D \sin A)^{1/2}$$

Figure 2.

Sequence of events as the casters of an occupied wheelchair (without footrests) drop off a top stair. After the casters strike the first step (B), the chair continues to rotate forward in a half-somersault. For the safety of the subject, he was permitted to sit crouched on the seat and to gently touch the stair rails on either side. When thrown from the chair, the subject landed in a pool and a rope prevented the chair from landing on top of him (C,D).

where TS is the theoretical speed of the wheelchair (m/s), D is the distance up the ramp (m), and $\sin A$ is the sine of the angle of the slope (degrees). On the basis of this and some pilot trials, a ramp angle of 3 degrees was selected as likely to provide an appropriate range of speeds.

However, on the assumption that there would be rolling resistance (3), a pair of infrared photoelectric gates a fixed distance apart on the flat platform was used to turn a timer on and off. This gave the time elapsed (to the nearest 0.01 s) for the wheelchair to travel the distance and allowed us to calculate the actual speed (m/s). The ramp provided

very reproducible threshold speeds ($r=0.97$) for the 20 subjects. The measured speeds were generally slower than the theoretical speeds, with mean (± 1 SD) differences of $0.17 (\pm 0.19)$ m/s at the slower speeds (without the device) ($p<0.001$), and $0.75 (\pm 0.09)$ m/s at higher speeds (with the device) ($p<0.0001$).

Procedure

The 20 subjects descended the ramp by gravity alone, with and without the stair-safety device in place (in balanced order). The wheelchair brakes were used as the release mechanism. The 11-cm

Figure 3.

The prototype stair-safety device, shown in the unengaged (top) and engaged (bottom) positions. Note that in the engaged position the rear wheels have lifted from the floor in a partial tip.

vertical drop at the end of the level platform was used to grade the results of each trial on a three-point ordinal scale (6): “no tip” if the rear wheels did not leave the platform, a “partial tip” if the rear tires lifted from the platform transiently, and a “full tip” if the chair went over the vertical drop such that the footrests contacted the floor below.

The starting position of the occupied wheelchair was moved up the ramp, in 10 cm increments, until a full tip occurred. The threshold distance required for full tipping was then found more accurately by using the 5 cm intervals. The subject repeated the trial from the threshold distance up the ramp to ensure reproducibility. The threshold speeds corresponding to these distances were calculated by using the photoelectric gates.

Statistical analysis

We compared the threshold speeds with and without the device in place by means of a matched-pairs *t*-test, and we used correlation coefficients to assess the influence of height and weight on the threshold speeds and to look for a relationship between the threshold speeds with and without the device in place. Statistical significance was defined as $p < 0.05$.

RESULTS

Without the device in place, the occupied wheelchair tipped fully at the lowest speeds that could be generated with the 3-degree ramp; there were no partial tips. At slower speeds than those measurable, the wheelchair would come to a stop between the photoelectric gates. The mean (± 1 SD) threshold speed causing a full tip was $0.38 (\pm 0.04)$ m/s. With the stair-safety device in place, the speed necessary to induce a full tip was $0.77 (\pm 0.06)$ m/s. Each subject's results are shown in **Figure 4**. The mean difference between the threshold speeds with and without the device in place was $0.39 (\pm 0.07)$ m/s ($p < 0.0005$). The threshold speed with the device in place did not correlate significantly with the subjects' height, weight, or tipping speed without the device in place. The chair frame showed no signs of collapse or fatigue despite the repeated testing.

Figure 4.

The threshold speed required to fully tip an occupied wheelchair when the casters drop off a stair, with and without the stair-safety device in place. The individual and mean (± 1 SD) values are shown.

DISCUSSION

The prototype device significantly increased the threshold speed necessary to induce a full tip. It can be speculated that the patients at greatest risk of a fall down a flight of stairs are those who are confused or have poor vision, and are therefore likely to be moving slowly. However, tips can occur at faster speeds even with this device in place. Some individuals who are moving quickly enough to tip fully with the device in place might nevertheless be helped indirectly, as the device appeared to slow down the wheelchair enough to give the wheelchair occupant a chance to grab the stair railings and thus prevent an accident. Raising the clearance for thick

carpet, independent obstacle-climbing, and outdoor use would render the device less effective.

A variant of this device might also be of use in preventing individuals in other wheeled devices (e.g., baby walkers [5]) from falling down stairs. Such walkers accounted for an estimated frequency of emergency-room visits in excess of 10,000 for 1980 in the U.S.; a follow-up survey revealed that 54 percent of these accidents resulted from falls down stairs (6). Alternative approaches to stair safety, such as better marking of stairwells or ledges, should also be pursued (9).

Limitations of this study include the use of able-bodied subjects and a single conventional wheelchair. Some actual wheelchair users have lower-extremity atrophy or amputations that may alter the location of their center of mass, and wheelchairs vary widely in their stability (7,8). An evaluation of this device by a wheelchair-using population should also provide valuable insights. The safety and efficacy of this device will not have been clearly demonstrated until such an evaluation takes place.

The prototype device used in the study, while sufficient to test our hypothesis, will need to be refined. Potentially useful improvements include easier removability and adjustability of clearance, decreasing its weight, putting rubber or plastic tips on the contact surface (to avoid slippage and prevent floor damage), and possibly attaching the device to the caster yoke so that it could work more effectively if the caster is not straight forward when dropping off a stair or ledge.

Despite the limitations of this study and the necessity for improvements in the prototype, this preliminary study suggests that such a wheelchair feature might improve the safety of wheelchairs in conditions involving inadvertent loss of caster support, as when they drop off a stair or ledge.

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