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Wheelchair stability: Effect of body position

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Abstract—When a wheelchair user reaches and leans, the static stability decreases in the direction of the lean and increases in the opposite direction. The purpose of this study was to determine the extent of this effect. We studied 21 nondisabled subjects in a representative wheelchair, measuring the static forward, rear, and lateral stability on a tilting platform. Reaching and leaning away from the tip added stability, with mean increases ranging from 9.1% to 124.3% of the neutral-position values, whereas reaching and leaning toward the tip reduced stability, with mean decreases ranging from 25.2% to 52.3% ($p<0.0001$). The stability range ("away" minus "toward") varied from 52.4% to 149.5%. Reaching forward had a greater effect on stability than did reaching back or to the side. Wheelchair users with the ability to control their body positions can profoundly affect the stability of their wheelchairs, a factor that should be considered in wheelchair selection and training.

Key words: *rehabilitation, safety, wheelchair.*

INTRODUCTION

There is an average of about 36,000 wheelchair-related injuries a year in the United States that are serious enough for the injured person to seek attention at an emergency room, and this rate is rising (1). About 75 percent of these injuries are due to tips and falls. Similarly, tips and falls were involved in 77.4 percent of 770 fatal wheelchair-related deaths recorded by the United States Consumer Product Safety Commission (2). About 47 percent of noninstitutionalized users of manually propelled wheelchairs have sustained an injury due to a tip or fall, or about 5 percent of users per year (3).

Experienced wheelchair users with sufficient range of motion, coordination, and strength will alter their postures (e.g., leaning forward when going up a slope) to reduce the likelihood of tipping. However, when wheelchair users lean to reach an object or to relieve pressure, they may inadvertently tip their chairs over (4,5). A number of studies have shown that the position of the combined center of gravity (CG) of the wheelchair and occupant has an important effect on stability (6–10).

Although it is self-evident that reaching and leaning decrease the static stability in the direction of the lean and increase the stability in the opposite direction, there are no reports in the published literature that document the extent of this important effect. The object of this study was to determine the extent of the effect of body position on wheelchair stability.

METHODS

Subjects

We studied 21 nondisabled subjects (11 females and 10 males) with their informed consent. Their mean (SD) age, height, and weight were 25.0 (3.7) years, 173.1 (8.3) cm, and 72.3 (13.2) kg. We studied nondisabled subjects rather than actual wheelchair users

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because some wheelchair users (e.g., those with amputations or with heavily muscled upper bodies) have variations in their body composition that affect stability. Also, limitations in range of motion, balance, or strength limit the ability of some users to achieve and sustain the body positions required for this study.

Wheelchair

We know from earlier reports that a wheelchair's specifications affect stability (4,8–10). But, because testing a wide range of wheelchairs would have been impractical, and because the focus of this study was on how body position (not wheelchair type) affects stability, we chose to use a single, representative wheelchair. In so doing, we controlled one source of variability. Each subject was studied in the same 15.9-kg wheelchair (an Invacare Action ST, Invacare, Elyria, OH). The rear-wheel diameter was 61 cm, and the caster diameter 15 cm. Each of the tires was pneumatic and was inflated to the manufacturer's recommended pressure. The rear-wheel axle was in the highest and most posterior of the available positions, and the upper border of the chair-back upholstery was 40 cm above the intersection of the back-support upright and the chair frame. Standard tubular, desk-length armrests for this chair were used (24 cm above the seat frame). The seat cushion (5.1 cm of foam covered in vinyl) was one designed for the chair and had Velcro® strips underneath to secure it to the seat. A lap belt was attached to the back of the seat-upholstery frame. We used pipe clamps to limit motion between the seat-upholstery and chair frames to prevent the wheelchair from folding during lateral-stability testing.

Stability Testing

Static stability was measured according to the methods of the International Organization for Standardization (ISO) (11) on a tilting platform, the angle of which was measured with a digital inclinometer (SMARTLEVEL digital inclinometer, Wedge Innovations, Sunnyvale, CA) sensitive to the nearest 0.1°. The endpoint that defined the limit of stability was lift-off of the uphill wheels from the platform. A spotter limited the extent of the induced tip to a few degrees.

In a randomly balanced order, we tested forward, rear (brakes locked and unlocked), and lateral stability. The high reliabilities of testing for forward and rear stability have been previously reported (8,9,12). We determined the reliability of lateral-stability testing with 10 subjects: there was a strong correlation (r=0.91) and no significant difference (p=.34 on a matched-pairs t-test) between the test and retest results.

Forward stability. The chair faced downhill and the casters trailed backward. To prevent the chair from rolling or sliding downhill as the platform tilted, we braced the casters against a barrier.

Rear stability. The chair faced uphill, and the casters trailed backward. For testing with the brakes locked, we placed each rear wheel on a friction pad (with a coefficient of friction [13] of > 0.48) to prevent rear slips, and placed a slide restraint a few cm downhill to limit the extent of any translational instability that might occur. To measure rear stability with the brakes unlocked, we braced the rear wheels against a barrier to prevent rolling.

Lateral stability. The chair faced 90° to the direction of tilt, and the casters trailed uphill. A barrier prevented the downhill caster from rolling. The rear wheels were locked and placed on friction pads with a nearby slide restraint.

Body Position

Each subject tightened the lap belt around his or her waist to the extent comfortably tolerated. The feet were positioned so that the heels were braced against the heel loops at the rear of the footrests. We tested each subject (in a randomly balanced order) in a neutral position, and while he or she reached and leaned forward, backward, and to the side (**Figure 1**).

Neutral position. The subject sat upright with the hands grasping the anterior parts of the armrests.

Reaching and leaning forward. The subject bent forward at the hips, touching the toes and looking at the feet as if tying his or her shoelaces (i.e., "toward" a forward tip and "away" from a rear tip).

Reaching and leaning backward. Each subject placed his or her nondominant hand on the armrest and looked at the dominant hand while reaching and leaning back as far as possible in the midline over a countertop-height bar 78.8 cm above the platform (14): toward a rear tip and away from a forward tip.

Reaching and leaning to the side. Each subject reached and leaned sideways as far as possible with the dominant hand over the countertop-height bar while the other hand grasped the ipsilateral armrest (i.e., reaching and leaning toward a dominant-side lateral tip and away from a nondominant-side tip). We chose not to test stability while subjects were reaching and leaning in the nondominant direction—there was only a clinically

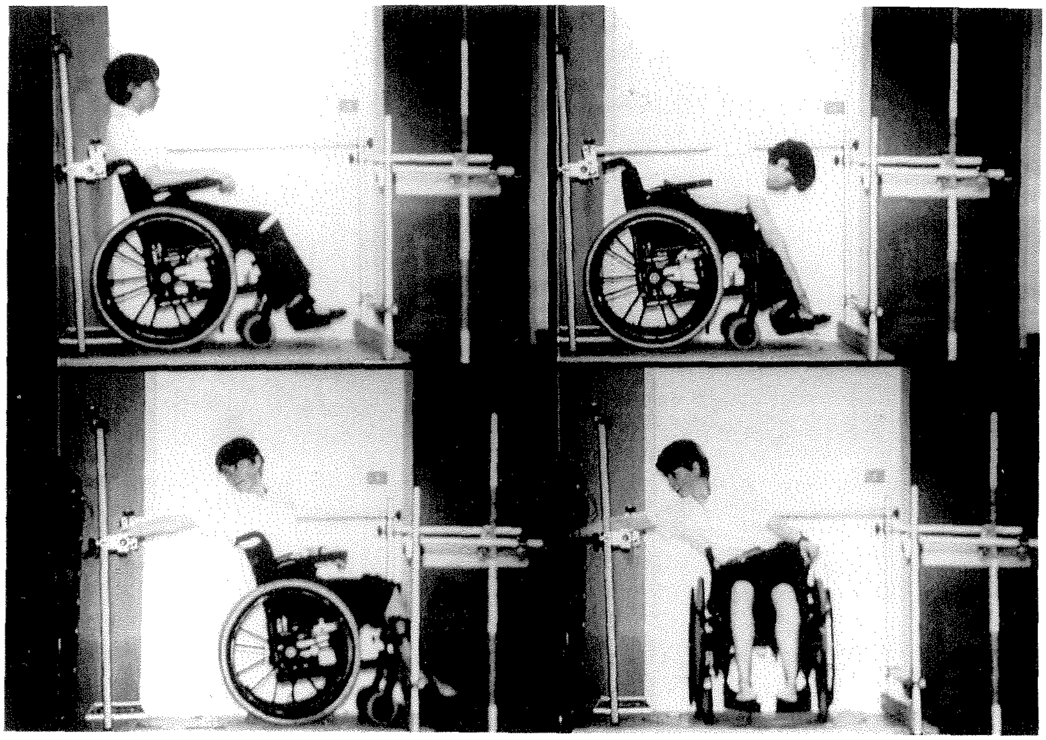

Figure 1.
Body positions used in the study: neutral (top left), and reaching and leaning forward (top right), backward (bottom left), and to the side (bottom right).

insignificant asymmetry (a 0.3 or 0.4° mean difference, with the dominant-side value greater; $p < 0.03$ on a matched-pairs *t*-test) in lateral stability with the subjects in the neutral position. The neutral reference value chosen for lateral-stability comparisons was that for a tip to the dominant side.

Statistical Analysis

Comparisons among the three stability values (neutral, toward, and away from the expected tip) for each of the four settings (forward, rear-locked, rear-unlocked, and lateral stabilities) were made by means of single-tailed matched-pairs *t*-tests on Microsoft Excel software. To reduce type-1 error, we applied Bonferroni corrections to all *p* values. Statistical significance was defined as $p < 0.05$.

RESULTS

The results are shown in **Table 1** and **Figure 2.** Reaching forward had a greater effect on stability than did reaching back or to the side. The mean increases in stability while subjects reached and leaned away from the tip ranged from 9.1 percent to 124.3 percent of the neutral-position values. The mean decreases in stability, while subjects reached and leaned toward the tip, ranged from 25.2 percent to 52.3 percent of the neutral-position values. The stability range (away minus toward), expressed as a percentage of the neutral-position values, varied from 52.4 percent to 149.5 percent. Rear stability was greater without brakes than with the brakes locked—the mean differences in the neutral, away, and toward posi-

Table 1.
Effect of body position on the static stability of a wheelchair (n = 21).

Direction	Body Position	Stability Mean	Away Mean Difference	Neutral Mean Difference
Forward				
	Away	26.5 (2.1)		
	Neutral	24.3 (1.6)	−2.2 (1.3)	
	Toward	11.6 (2.0)	−14.9 (1.6)	− 12.7 (1.1)
Rear (with brakes)				
	Away	24.0 (1.1)		
	Neutral	10.7 (1.0)	−13.3 (1.0)	
	Toward	8.0 (1.5)	−16.1 (1.8)	− 2.7 (1.1)
Rear (without brakes)				
	Away	40.9 (1.9)		
	Neutral	19.1 (2.5)	−21.8 (1.7)	
	Toward	14.1 (3.4)	−26.8 (3.0)	− 5.0 (2.7)
Lateral				
	Away	26.1 (1.2)		
	Neutral	21.4 (0.9)	−4.7 (1.0)	
	Toward	14.9 (1.6)	−11.2 (1.8)	− 6.5 (1.0)

The values shown are in degrees, with the standard deviations in parentheses. All mean differences were significant on matched-pairs t tests at $p < 0.0001$, after Bonferroni corrections.

tions were 8.4 (1.8)°, 16.9 (1.3)°, and 6.1 (2.4)°, respectively ($p < 0.0001$).

DISCUSSION

The results demonstrate that the extent of the effect on wheelchair stability of reaching and leaning by a wheelchair occupant is a profound one, decreasing stability in the direction of the lean and increasing stability in the opposite direction. The magnitude of the effect varied with the direction of the lean; reaching and leaning forward had the greatest effect on stability. This may have been, in part, because we allowed both arms to reach forward, whereas the subjects reached behind or to the side with only one arm.

We also speculated that the effects of reaching and leaning in the rear and lateral directions would be

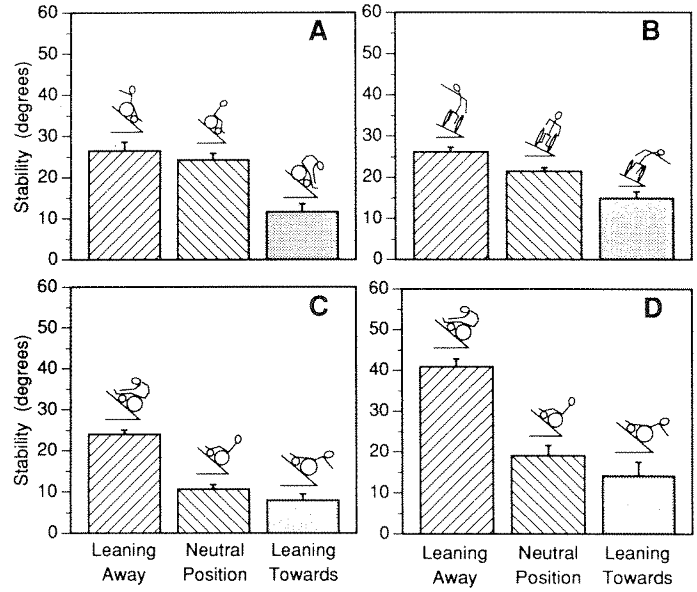

Figure 2.
Static stability in the neutral body position and while reaching and leaning toward and away from the expected tip: forward (A), lateral (B), rear with brakes locked (C), and rear with brakes unlocked (D). Mean values (+1SD) are shown.

greater if the backrest height was lower or if the armrests were removed. With a single subject, we tested this hypothesis by removing the backrest and armrests for appropriate components of the protocol. As expected, reaching and leaning back reduced rear stability (with the brakes unlocked) by 43.0 percent of the neutral-position values and increased forward stability by 65.3 percent (compared to the 26.2 percent and 9.1 percent found in the formal study with the backrest in position). The clinical implication is that, when choosing the height of the backrest, its potential effect on the user's stability should be taken into consideration. A low backrest permits a wheelchair user to further enhance the forward stability of the wheelchair by leaning backward. However, if a wheelchair user who is unfamiliar with the effect of body position on rear stability were to lean and reach backward in a wheelchair with a low backrest, the wheelchair could tip over backward. The extent to which this risk is a function of backrest height is an area requiring further research.

When the single subject (noted above) reached and leaned to the side, without armrests on the chair, the lateral stability in the direction of the lean was decreased by 28.9 percent and lateral stability increased in the other direction by 29.0 percent (compared to the 30.4 percent and 22.0 percent found in the formal study with the armrests in position). The presence of the armrests does not appear to explain why reaching and leaning to the side affected stability less than reaching and leaning forward or back.

Rear stability with the brakes locked was less than with the brakes unlocked, as has been previously reported by Cooper et al. (15). This was expected because stability is affected by the position of the axis of rotation—stability is equal to the arctangent of the ratio between the horizontal and vertical distances from the system CG to the axis of rotation (10). The axis of rotation for brakes-unlocked testing runs through the rear axles. For the locked-brakes rear-stability test, the axis is much lower (at the contact point between the rear wheels and the ground). (When modelling rear stability with the brakes unlocked, the masses of the rear wheels must be excluded, so the CG is higher and farther forward than it is with the brakes locked.) The effect on stability of locking the brakes is important in the context of the current study because it confirms that wheelchair users reaching and leaning backward are less likely to tip over if they do so with the brakes unlocked than with them locked—a conclusion that might not be self-evident to some wheelchair users or to the clinicians training them.

The results of this study will need to be validated with wheelchair users in their own chairs. To generalize from our preliminary work to all wheelchair users and all wheelchairs is a worthy matter for future investigation, but was beyond the scope of this study. The type of tradeoff between reliability and generalizability that we made is regrettable, but necessary in studies of this type.

We used only static-stability measures, whereas some of the instabilities that are important (e.g., the effect on stability of a user leaning forward while wheeling up a ramp) occur in a dynamic situation. However, we believe that confining ourselves to static testing was reasonable because 1) there are no national or international standards for testing the dynamic stability of manually propelled wheelchairs, 2) the tests that are available for dynamic testing (8,10) might have been dangerous with the subjects in the positions under study, and 3) Majaess et al. (10) have demonstrated a good correlation between values for static and dynamic stability.

CONCLUSION

Wheelchair users with the ability to control their body position can profoundly affect the stability of their wheelchairs, a factor that should be considered in wheelchair design and in the process of wheelchair selection and training.

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