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A Review Article

A technique for the determination of center of gravity and rolling resistance for tilt-seat wheelchairs

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Abstract—A balance platform setup was defined for use in the determination of the center of gravity in the sagittal plane for a wheelchair and patient. Using the center of gravity information, measurements from the wheelchair and patient (weight, tire coefficients of friction), and various assumptions (constant speed, level-concrete surface, patient-wheelchair system is a rigid body), a method for estimating the rolling resistance for a wheelchair was outlined. The center of gravity and rolling resistance techniques were validated against criterion values (center of gravity error = 1 percent, rolling resistance root mean square error = 0.33 N, rolling resistance Pearson correlation coefficient = 0.995). Consistent results were also obtained from a test dummy and five subjects. Once the center of gravity is known, it is possible to evaluate the stability of a wheelchair (in terms of tipping over) and the interaction between the level of stability and rolling resistance. These quantitative measures are expected to be of use in the setup of wheelchairs with a variable seat angle and variable wheelbase length or when making comparisons between different wheelchairs.

Key words: *biomechanics, center of gravity, rolling resistance, tilt-seats, wheelchairs.*

INTRODUCTION

In the past decade, wheelchairs have undergone substantial changes which make these devices easier to propel, more comfortable, and capable of being modified to meet individual specifications. While these improvements can provide many benefits to the patient, the clinician has not been provided with quantitative measures to aid in the optimal setup of these modifiable wheelchairs.

Two wheelchair-setup criteria which lack quantifiable measures are seat angle and wheelbase length. Wheelchairs with adjustable seat angles allow the center of gravity of the patient-wheelchair to move forward or backward in the sagittal plane. This tilt feature may lead to backward tipping problems if the wheelbase is not adequately adjusted (especially for amputees). Cooper (2) described a method similar to du Bois-Reymond (3) for determining the center of gravity of a wheelchair; however, the equations used for the calculations did not include the inertial parameters of the balance board (the board on which the wheelchair is supported while the center of gravity is determined). By modifying the seat angle and wheelbase, it is also possible to change the rolling resistance of a wheelchair (5,6). By knowing the center of gravity and rolling resistance, the clinician is able to adjust the wheelchair so that a minimum amount of effort is needed for propulsion, to better evaluate the possibility of backward tipping, to compare objectively between wheelchairs, or to compare different wheelchair-tire configurations on the basis of rolling resistance. Mathematically, it has been shown that by positioning the center of gravity of the patient-wheelchair system closer to the rear axle, the rolling resistance of the system will decrease, since the rolling resistance of the large rear wheel is less than that of the small front wheel (1,7).

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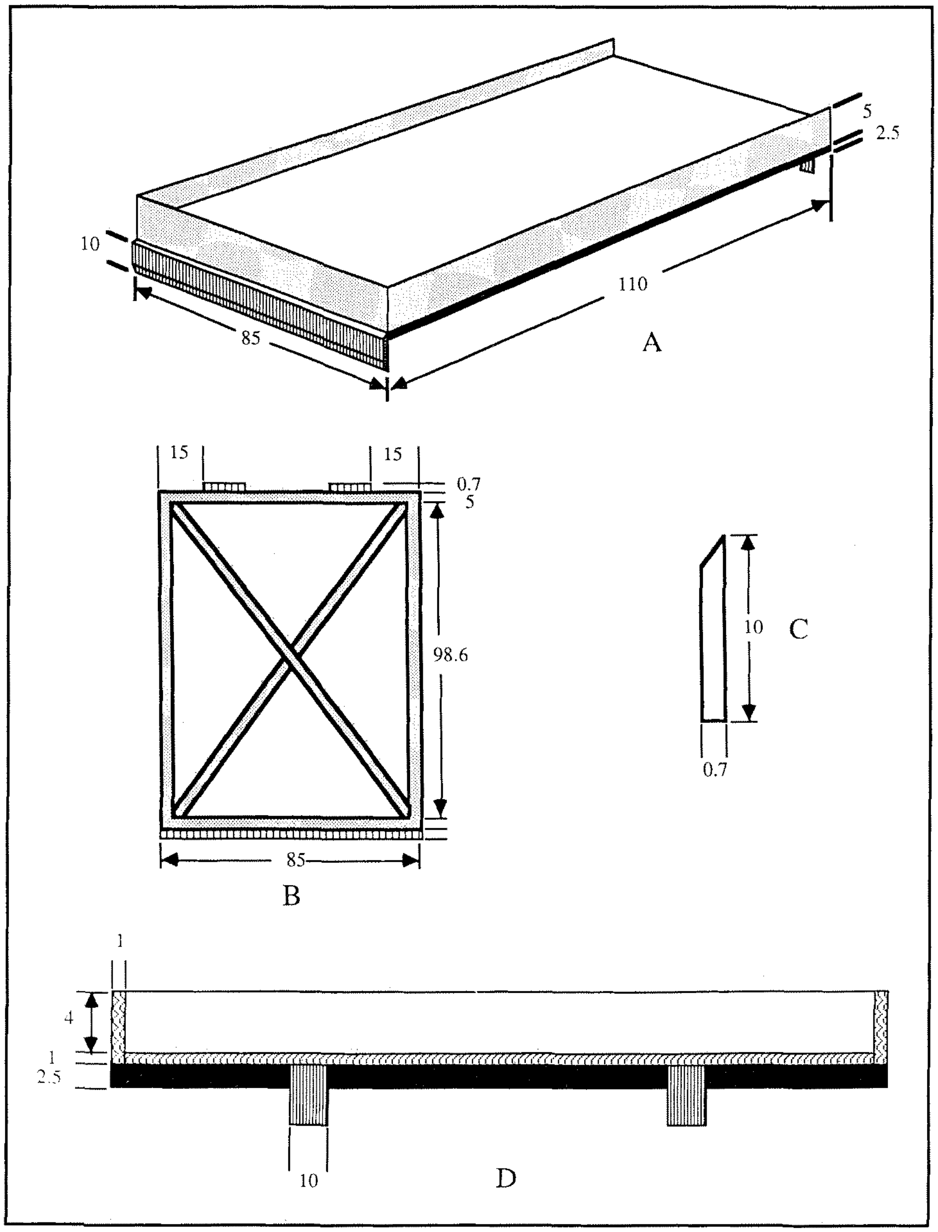

Figure 1.
Balance platform dimensions. A = general view, B = bottom view (including aluminum frame), C = tapered steel plate side view, D = front view. All units in centimeters.

This study describes a quick, easy method for determination of the patient-wheelchair center of gravity in the sagittal plane and the rolling resistance of the patient-wheelchair system.

METHODS

Center of gravity

Equipment and Data Collection

In order to determine the center of gravity for the patient-wheelchair system, a balance platform was constructed in a manner similar to du Bois-Reymond (3). A support frame was built using 2.5 cm square aluminum tubing and covered by 1.0 cm-thick plywood (**Figure 1**). Two tapered steel plates were welded to the narrow ends of the aluminum frame so that the platform was level when resting on the tapered edges. These plates were used so that the contact point between the platform and the support surface was minimized, thereby providing a pivot point on each end. In order to reduce the balance platform weight, the front plate can be replaced by two 10 cm-wide tapered steel plate sections. A 1 $\times$ 5 cm plywood border was attached on the sides and back of the plywood surface to ensure that the wheelchair would not easily roll off the side of the balance platform.

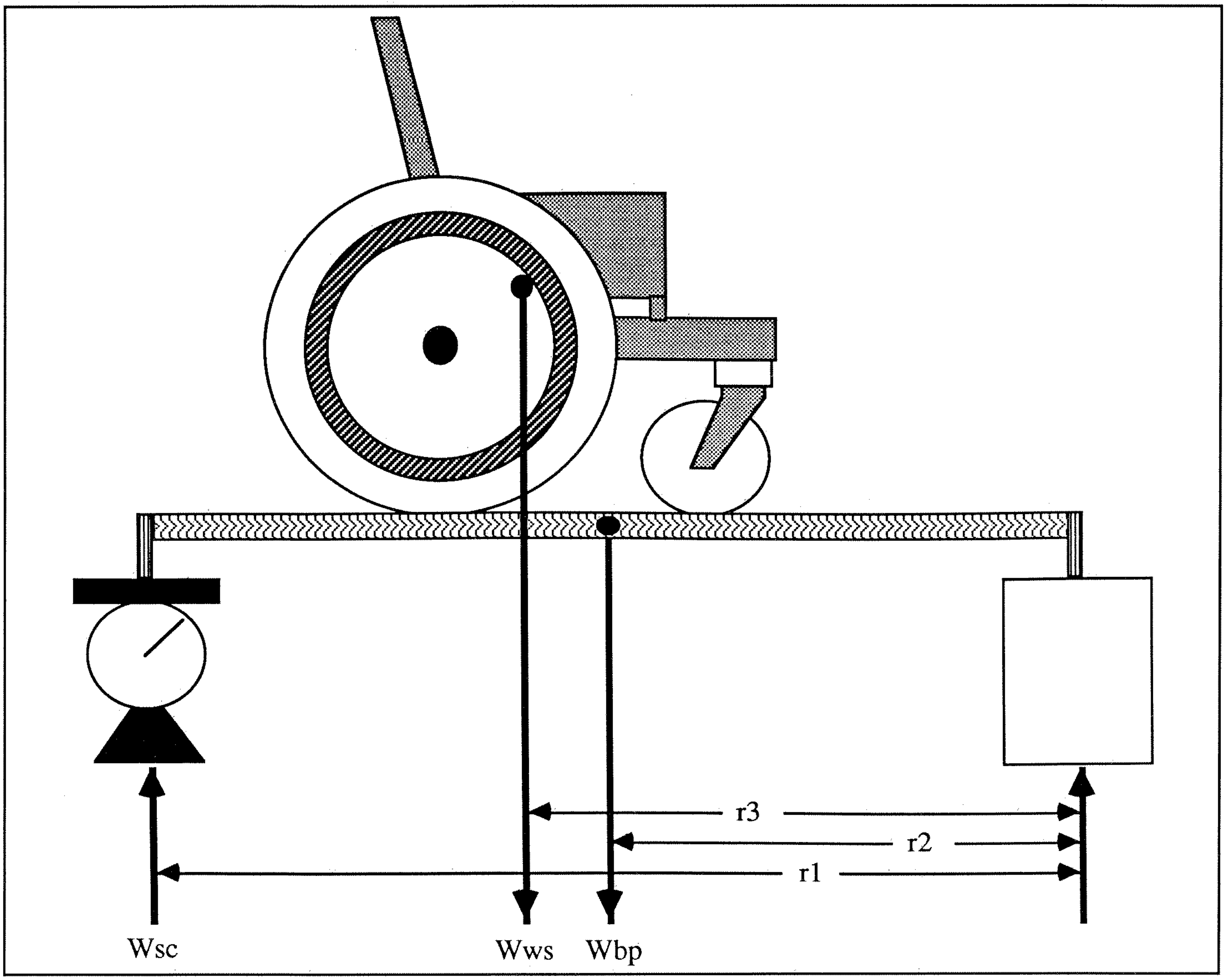

Figure 2.
Center of gravity test setup. W_{sc} = weight from the scale, W_{ws} = weight of the wheelchair and the patient, W_{bp} = weight of the balance platform, r_1 = distance between the two pivot points, r_2 = distance from the pivot point to the balance platform center of gravity, r_3 = distance from the pivot point to the patient-wheelchair center of gravity.

Once the balance platform was completed, its center of gravity was measured by balancing the platform on the edge of a tapered steel plate (the plate was oriented perpendicular to the long side of the balance platform) and the distance from the rear board plate to the balance point was measured. The weight of the balance platform, the weight of the wheelchair, the weight of the patient, and the length from the front axle to the rear axle (wheelbase length) were also measured for use in the center of gravity calculations.

Data collection with this system involved positioning the balance platform with one of the steel plates resting on a scale and the other plate resting on a surface equal in height to the scale base (thereby keeping the platform level). A straight metal piece (alignment bar) was placed on top, and perpendicular to, the board edges at a distance of 30 cm from the rear of the board to assist in positioning the wheelchair. Using a small ramp, the wheelchair was backed onto the platform until the rear wheels touched the alignment bar. The front wheels were then straightened and oriented for forward motion. The distance between the rear wheel axle and the rear plate was then measured

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for use as a reference point for the center of gravity position (this measurement will only have to be done once for a pair of wheels, assuming that the position of the alignment bar is consistent) and the alignment bar was removed. Once the patient was stationary, a scale reading was taken and recorded.

The balance platform technique was validated using an 80 lb mass with a known center of gravity position. The center of gravity of the mass was positioned at distances of 10, 40, and 70 cm from the end of the platform. The center of gravity positions were subsequently obtained, using the balance platform, and compared to the criterion values.

Calculations

The center of gravity in the patient's sagittal plane was calculated using the static moment equation for the system:

$$\Sigma M_p = 0$$
$$r_3\, W_{ws} + r_2\, W_{bp} - r_1\, W_{sc} = 0 \qquad [1]$$

where,

r_3 = distance from the pivot point to the patient-wheelchair center of gravity.
r_2 = distance from the pivot point to the balance platform center of gravity.
r_1 = distance between the two pivot points (steel plates).
W_{ws} = weight of the wheelchair and the patient.
W_{bp} = weight of the balance platform.
W_{sc} = weight from the scale.
M_p = moment about the pivot point.

By solving for the distance from the scale to the patient-wheelchair center of gravity and subtracting the distance from the scale pivot point to the rear axle (**Figure 2**), the distance from the rear wheel axle to the patient-wheelchair center of gravity can be obtained.

$$R_{rw} = \left(r_1 - \left(\frac{r_1\, W_{sc} - r_2\, W_{bp}}{W_{ws}} \right) \right) - r_{rw} \qquad [2]$$

where,

R_{rw} = distance from the rear wheel axle to the patient-wheelchair center of gravity.
r_{rw} = distance from the pivot point to the rear wheel axle.

This information can be organized into an easy to read chart format or used in a microcomputer program (**Appendix A**).

Rolling resistance

In order to calculate the rolling resistance of the wheelchair certain assumptions were made:

- The patient-wheelchair system can be considered a rigid body.
- Wheelchair wheels are traveling at a constant angular velocity.
- The patient-wheelchair system is traveling on a level, concrete surface.
- The friction at the wheel axle is negligible.
- The tires have been inflated to manufacturers' specifications.

Using these assumptions and the equations of motion for the system, a good estimate of the rolling resistance can be obtained.

Coefficient of Friction of Tires

One present limitation of this technique for determining the wheelchair rolling resistance is the lack of information on the coefficient of rolling friction for wheelchair tires. This information is necessary for the solution of the rolling resistance equations. At the present time, these coefficients may be obtained from some tire manufacturers, with the method described by Gordon, *et al.* (4), or by rolling the wheelchair over a force platform.

The force platform technique involves pushing a wheelchair, loaded with at least 50 kg, over a force platform so that only one of the front and back wheels crosses the force platform surface. It is very important to ensure that the wheelchair travels at a constant speed while in contact with the force platform. The Fx, Fy, and Fz force vectors are sampled during this time at a sufficiently high rate (at least 200 Hz). The average force values for the periods where only the front or back wheel is on the force plate are calculated and entered into Equation 3 for calculation of the rolling coefficient of friction:

$$\mu = \frac{\sqrt{F_x^2 + F_y^2}}{F_z} \qquad [3]$$

where,

μ = coefficient of rolling friction
F_x, F_y = horizontal force components
F_z = vertical force component

Since the rolling coefficient of friction is velocity dependent, the wheelchair velocity should be calculated by obtaining the time of force plate contact (t) from the sampled data, the wheelbase length (L_{wb}), and the force plate length (L_{fp}):

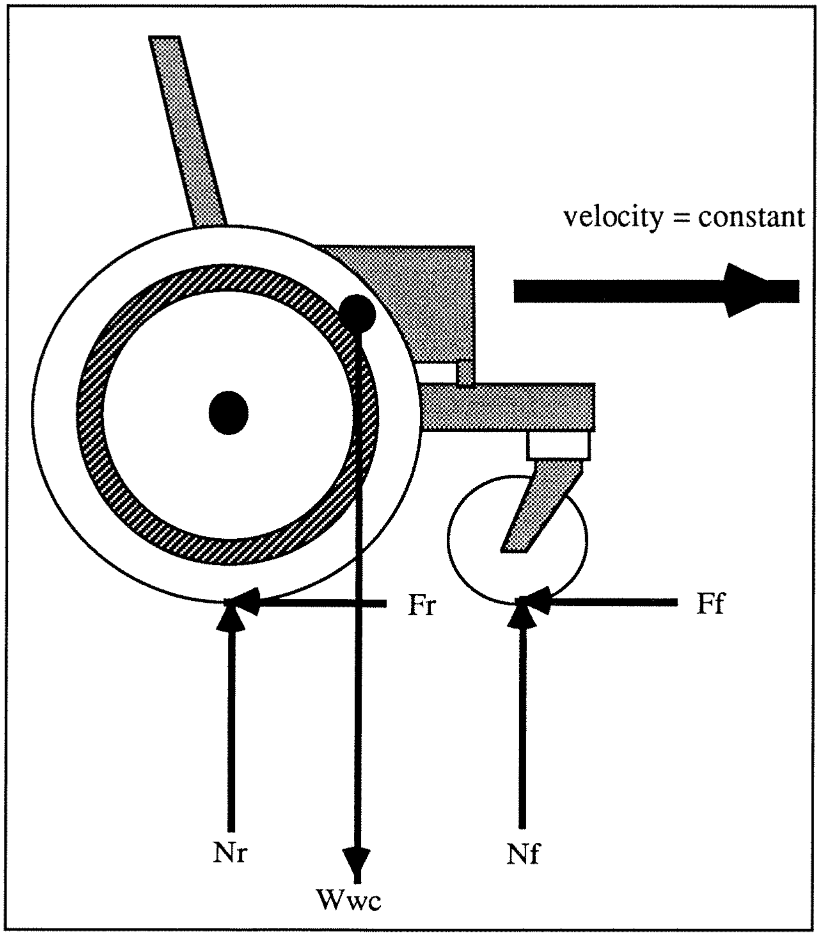

Figure 3.
Free body diagram for the calculation of rolling resistance. F_f = front wheel friction, F_r = rear wheel friction, W_{wc} = weight of the loaded wheelchair, N_r = rear wheel normal force, N_f = front wheel normal force.

$$v = \frac{(L_{wb} + L_{fp})}{t} \quad [4]$$

This velocity value should be approximately the same as the usual patient-wheelchair propulsion speed (2-4 km/h). Some error may occur due to the slowing down of the wheelchair as it crosses the platform; however, the amount of deceleration can be checked by comparing the average velocity values between the front and back wheels (ideally, these values should be the same).

Calculations

The solutions of the equations for the wheelchair rolling resistance involve obtaining the coefficient of rolling friction for the tires, the distance from the rear wheel axle to the patient-wheelchair center of gravity (using the balance platform technique), the weight of the patient-wheelchair, and the wheelbase length (**Figure 3**). These values are used in Equations 5 and 6 to calculate the rolling friction for one front and one rear tire.

$$F_f = \mu_f \times \left(\frac{r_{cg} \times W_{wc}}{L_{wb}} \right) \quad [5]$$

$$F_r = \mu_r \times \left(W_{wc} - \left(\frac{r_{cg} \times W_{wc}}{L_{wb}} \right) \right) \quad [6]$$

where,
F_f = front wheel friction
F_r = rear wheel friction
μ_f = coefficient of rolling friction for the front wheel
μ_r = coefficient of rolling friction for the rear wheel
r_{cg} = distance from the rear wheel axle to the center of gravity
W_{wc} = weight of the loaded wheelchair
L_{wb} = wheelbase length

The total rolling friction for the wheelchair is obtained by adding the front and back wheel rolling frictions and multiplying this value by 2.

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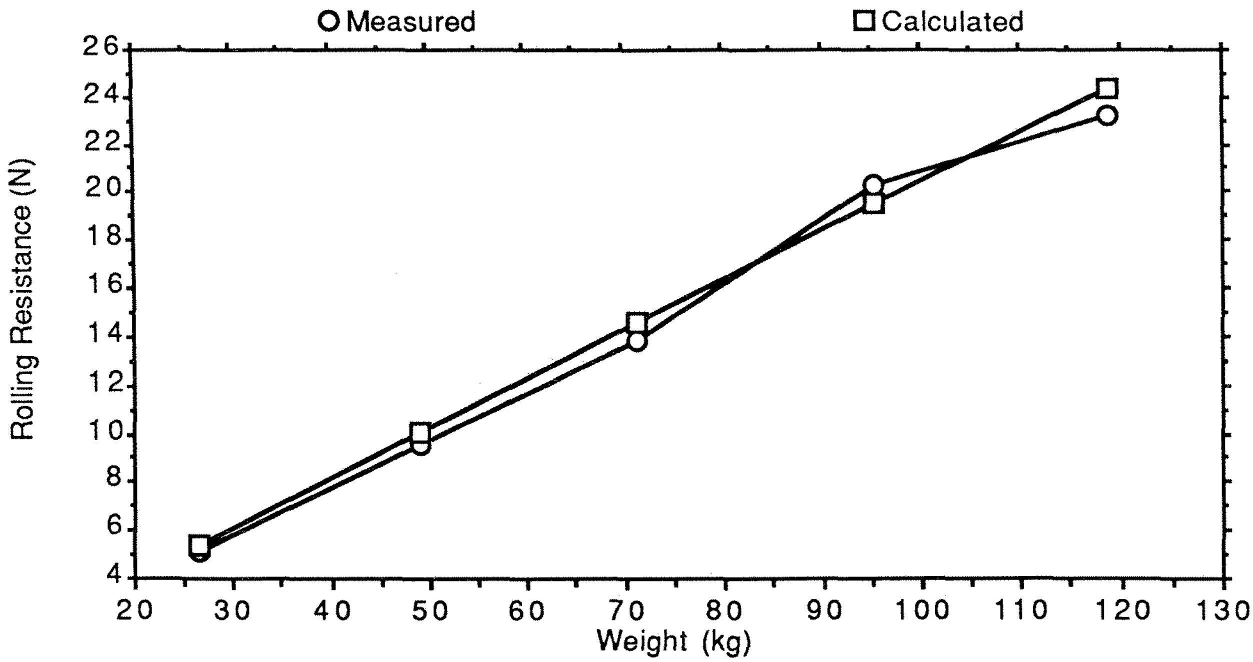

Figure 4.
Measured (treadmill test) and calculated rolling resistance values for a wheelchair in the seat-up position.

Validation

In order to validate the technique for determining wheelchair rolling resistance, calculated rolling resistance values were compared with measured rolling resistance values for the entire chair. The total rolling resistance for the wheelchair was obtained by securing a load cell to the front of the wheelchair and to a structure in front of a treadmill. After locking the front casters in the forward position (to ensure that the wheelchair would run straight), the wheelchair was positioned on the treadmill such that the load cell functioned along the midline of the wheelchair and the midline of the treadmill. While running at 2.5 km/h, the actual rolling resistance value for the wheelchair was obtained by reading the voltage output from the strain gauge and converting this value to newtons. The previous steps were repeated for weights of approximately 25 to 120 kg. The measured rolling resistance values were compared to the calculated values (obtained using the center of gravity technique and the equations of motion for the wheelchair system) using root mean square (RMS) and Pearson product-moment correlation statistics.

In order to test the system in a more realistic environment, center of gravity and rolling resistance were determined for a test dummy (ISO Standard 7176-11) and for five bilateral above-knee amputee subjects (three male and two female). All measurements were made using an Advanced Mobility Systems (AMS) tilt-seat wheelchair.

RESULTS

The calculated center of gravity values for the 80 lb mass were 9.4 cm, 39.8 cm, and 69.6 cm (criterion: 10 cm, 40 cm, 70 cm), thereby giving an average error of 1 percent. The validation procedure for rolling resistance produced a RMS value of 0.33 N (2 percent of full scale) and a correlation coefficient of 0.995 between the criterion and calculated values (**Figure 4**).

In terms of the evaluation involving the test dummy

Table 1.
Distance from the rear wheel axle to the center of gravity for the subject-wheelchair complex (in centimeters) and the subject-wheelchair weight (in kilograms).

	Weight (kg)	Seat Up (cm)	Seat Back (cm)
Dummy	100.00	17.1	13.3
Subject 1	103.75	16.3	10.0
Subject 2	129.66	22.9	14.8
Subject 3	91.18	18.8	12.5
Subject 4	73.41	18.9	14.0
Subject 5	83.64	20.3	14.5

Seat up is standard seating position; seat back corresponds to a seat angle of 116 degrees to the horizontal.

Table 2.
Rolling resistance values (in newtons) for the front wheel, rear wheel and the total of all four wheels of a tilt-seat wheelchair.

	Seat Up (N)			Seat Back (N)		
	Front	Rear	Total	Front	Rear	Total
Dummy	14.77	6.83	42.20	11.53	7.70	38.46
Subject 1	13.69	7.57	42.52	8.41	8.98	34.78
Subject 2	23.94	7.65	63.18	15.49	9.90	50.78
Subject 3	14.16	6.31	40.94	9.39	7.58	33.94
Subject 4	11.23	4.95	32.36	5.95	6.36	24.62
Subject 5	13.71	5.40	38.22	9.78	6.44	32.44

Seat up is standard seating position; seat back corresponds to a seat angle of 116 degrees to the horizontal.

and subjects, the results for the center of gravity calculations are in **Table 1** and the results for the rolling resistance calculations are in **Table 2**. The rolling resistance results are presented for one front wheel, one back wheel, and for all four wheels (total rolling resistance). Rolling resistance was assumed to be bilaterally equivalent.

DISCUSSION

Examination of the validation results for the center of gravity measurement technique showed an extremely low error (approximately 1 percent). This technique can, therefore, be considered valid for determining the center of gravity of a loaded wheelchair. The validity of the rolling resistance technique was also supported by an extremely high Pearson correlation coefficient and an extremely low RMS error (approximately 2 percent) between the measured and calculated values. The low errors found for both techniques were well within the necessary range for clinical evaluation and also indicated applications for research which involve the determination of center of gravity and/or rolling resistance (assuming the basic assumptions are met).

The evaluation of center of gravity and rolling resistance for the test dummy and bilateral amputee subjects produced the expected results (rolling resistance increased with body weight and decreased with seat tilt) (1,7). It should be noted that the rolling resistance values were not linearly related to body weight. This result is likely due to the variety of body types present over the five subjects and the effect of these body types on the position of the subject-wheelchair center of gravity.

Upon comparison of the pneumatic rear wheel rolling resistance values for the subjects with the results of Gordon, *et al.* (4), it was found that only a small difference occurred between values (difference in means = 0.9 N, Pearson correlation coefficient = 0.97). The slightly higher friction force found by Gordon could be due to the difference in test surfaces between the two studies (i.e., force platform surface vs. treadmill belt). There were no data available to compare with front wheel rolling friction.

Clinically, the application of this measurement tool has merit when addressing the relationship between rolling resistance, center of gravity, and rearward tip angle. Generally, it is acknowledged that a shorter wheelbase (i.e., rear wheels moved toward the front of the wheelchair) will reduce the rolling resistance and negatively affect stability (i.e., decrease in the rearward tip angle). These facts are directly related to the center of gravity position since, as the wheelbase is decreased, the center of gravity moves closer to the rear axle. This results in more weight being centralized over the rear wheels, thereby reducing the rolling resistance; however, when the wheelchair is tipped backward, the center of gravity does not have as far to move before the wheelchair passes the balance point (the point at which the center of gravity passes behind the rear axle). Similarly, a longer wheelbase will increase the rearward tip angle and increase the rolling resistance.

Based on wheelchair rearward stability, many clinicians choose the longer wheelbase format, believing this to be in the safest interests of the client. Although this may be the ideal solution for some patients, it should also be recognized that, apart from the decrease in maneuverability, the increase in rolling resistance may contribute to undue fatigue, pain in previously damaged joints or inflamed soft tissue, or contribute to degeneration of presently healthy structures through repeated loading over a long period.

By the utilization of center of gravity and rolling resistance information during the wheelchair setup process, the clinician will be able to decide on the wheelchair configuration which will promote safety but have the minimum sacrifice of function.

CONCLUSION

A method and device for determining the center of gravity for a patient in a wheelchair and estimating the rolling resistance of the wheelchair has been described. These tools are beneficial to the clinician for the setting up of tilt-seat wheelchairs, determining the best wheelbase length, and making comparisons between wheelchairs. These valid, quantitative measures are expected to help make the task of setting up wheelchairs consistent and more efficient.

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APPENDIX A

BASIC COMPUTER PROGRAM TO CALCULATE CENTRE OF GRAVITY AND ROLLING RESISTANCE

```
5    REM ** Program to Determine CofG and Rolling Resistance **
6    REM ** Replace given values in program with values specific to
7    REM ** your setup **
10   CLS
20   FLAG = 1
30   WHILE FLAG
40   INPUT "ENTER THE WHEELCHAIR-SUBJECT WEIGHT (LB)";WCWT
50   INPUT "ENTER THE SCALE READING (LB)";SCWT
60   NWCWT = WCWT/2.2*9.81:NSCWT = SCWT/2.2*9.81
70   BDLEN = 91.6 '** Board length **
80   BDCG = 52.6 '** Distance to board centre of gravity **
90   BDWT = 182.82 '** Board weight in newtons **
95   REM ** Calculate distance from the scale to the CofG **
100  R1 = BDLEN - ((BDLEN*NSCWT - BDCG*BDWT)/NWCWT)
110  R2 = 46.5 '** Wheelbase length **
120  D1 = 35 '** Distance from the scale to the rear axle **
130  R3 = R1-D1 '** Distance from the rear axle to the CofG **
140  PRINT "THE WHEELCHAIR COFG IS "R1" CM FROM THE SCALE"
150  PRINT "AND "R3" CM FROM THE REAR AXLE"
155  REM ** Calculate the rolling friction values **
160  UR = 0.011 '** Rear wheel coefficient of friction **
170  UF = 0.041 '** Front wheel coefficient of friction **
180  FF = UF * ((R3*NWCWT)/R2)
190  FR = UR * (NWCWT - ((R3*NWCWT)/R2))
200  PRINT:PRINT "FRONT WHEEL ROLLING FRICTION = "FF" N"
210  PRINT "REAR WHEEL ROLLING FRICTION = "FR" N"
220  PRINT:INPUT "DO YOU WANT TO PRINT THE RESULTS (Y/N)"; ZZ$
230  IF (ZZ$="Y") OR (ZZ$="y") THEN GOSUB 900
240  PRINT:INPUT "DO YOU WANT TO EXIT (Y/N)"; ZZ$
250  IF (ZZ$="Y") OR (ZZ$="y") THEN FLAG=0
260  WEND
270  END
900  LPRINT:INPUT "ENTER TRIAL TITLE"; TIT$
910  LPRINT CHR$(14);TIT$
920  D$=DATE:LPRINT "DATE: "D$:LPRINT
930  LPRINT "WHEELCHAIR-SUBJECT WEIGHT IS "WCWT" LB"
940  LPRINT "SCALE READING IS "SCWT" LB"
950  LPRINT "WHEELBASE LENGTH IS "R2" CM"
960  LPRINT "LENGTH TO REAR AXLE IS "D1" CM":LPRINT
970  LPRINT "THE WHEELCHAIR COFG IS "R1" CM FROM THE SCALE"
980  LPRINT "AND "R3" CM FROM THE REAR AXLE"
990  LPRINT:LPRINT "FRONT WHEEL ROLLING FRICTION = "FF" N"
1000 LPRINT "REAR WHEEL ROLLING FRICTION = "FR" N"
1010 FOR X=1 TO 5:LPRINT:NEXT X
1020 RETURN
```