WHEELCHAIR SAFETY, STANDARDS AND TESTING

3.1. Introduction

Standards have been developed for numerous products due to the concern of consumers, manufacturers and government for safety and the availability of quality products. Some industries regulate themselves, while others are regulated by state and/or federal agencies. Recently, there has been movement towards international standards because of a growing global economy.

3.1.1. Standard Tests

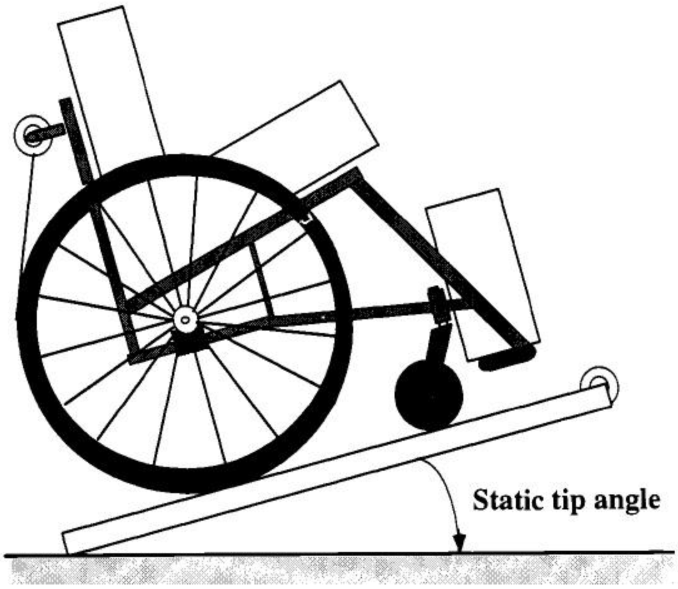
If a product is to be certified by a national or international organization, it must undergo and pass a series of standardized tests. A variety of tests are used to evaluate the safety and durability of devices. Tests are designed so that similar results can be achieved at any recognized test facility Manual and power wheelchairs are tested. The tests vary slightly depending on which type of product is being tested. The tests for all wheelchairs can be grouped into three categories***: (1) stability tests (static and dynamic), (2) strength tests (static, impact and fatigue) and (3) energy consumption tests.***

3.1.2. Normative Values

Once a wheelchair has been tested, the performance of the wheelchair must be evaluated against normative values for similar products. These values may be derived by manufacturers through testing several models of the same wheelchair or by testing a product line. Normative values for use by consumers, purchasers and manufacturers must be developed by testing several wheelchairs from a number of different manufacturers. Normative values must be developed for products designed for use in similar situations.

3.2. Static Stability

A simple measure of how stable and secure a wheelchair is during normal activities of daily living is to determine static stability parameters Wheelchairs are tested on a simple tilting platform. Wheelchair with a person or appropriate test dummy is rolled onto a tilting platform. Once in place, the incline of the platform is slowly increased until the wheelchair tips or slides. The tip angle is also measured in a similar manner with the loaded chair facing down the tilt platform and facing to the side of the tilt platform. These tests help to determine the static stability of the wheelchair while the person performs various activities of daily living.



3.2.1. A Geometric Approach to Static Stability

The geometric approach to stability analysis is primarily a qualitative method of examining the static stability of a vehicle. This approach should assist the reader who is not mathematically inclined in developing a more intuitive sense for the notion of stability of complex systems.

When a wheelchair is motionless on a flat surface, there are as many points of contact with the surface as there are wheels. If adjacent contact points are connected with lines, the footprint is constructed. The footprint of a three-wheeled chair is a triangle, whereas the footprint of a four-wheeled chair is a rectangle. For a wheelchair to be statically stable (i.e., when the chair and rider are not moving) the center of gravity of the rider wheelchair system must remain within the footprint. If the rider wheelchair system is tilted on a platform, then the perpendicular projections of the points of contact of the wheels with the platform onto the floor form the new footprint. One might imagine a rider wheelchair system sitting on a glass platform tilted with respect to the floor, a carpenter's square is placed on the floor directly below the point of contact of each wheel with the glass platform and a corresponding point on the floor.

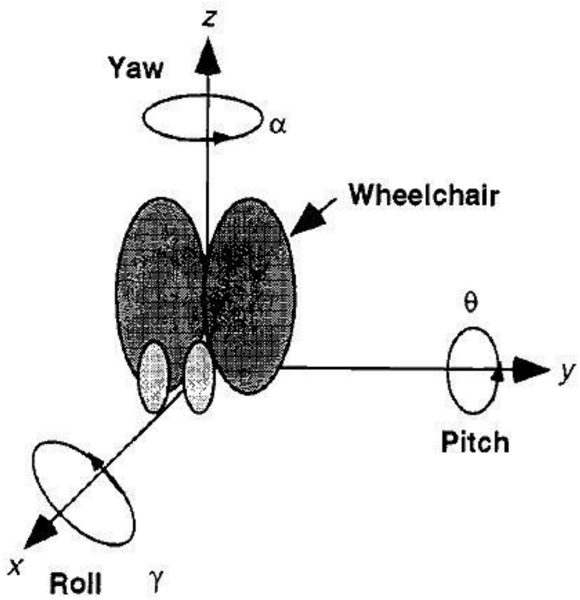


Figure *Coordinate system for wheelchair stability analysis.*

The degree of static stability is related to the area of the footprint. All other factors being equal, which is seldom the case, the larger the area of the footprint the greater the stability. One might interpret this to mean that if the area of the triangular footprint of a three-wheeled chair were made the same as the area of the rectangular footprint of a four-wheeled chair the chairs would be equally stable. This may not be true. If all of the other rider wheelchair dimensions were equal and the center of gravity were located in the geometric center of each respective footprint, the chairs would not have the same degree of stability in all directions. This is because the distance of the center of gravity from each edge of the respective footprints cannot be equal for three and four wheeled chairs as one is a triangle while the other is a rectangle.

3.3.1. Stability with Road Crown and Inclination

The effects of road crown and road inclination can be examined using coordinate transformations from the wheelchair coordinate frame to the world coordinate frame. The influence of gravity on the stability of the racing wheelchair is only dependent upon the wheelchair's orientation; hence the coordinate transformations are purely rotations. Road crown and inclination alters the projected height of the wheelchair/pilot system center of gravity and also the projected width of the wheelbase.

The coordinate transformation matrices are defined below.

$$R_{x,\gamma} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_\gamma & -s_\gamma \\ 0 & s_\gamma & c_\gamma \end{bmatrix} \quad R_{y,\theta} = \begin{bmatrix} c_\theta & 0 & s_\theta \\ 0 & 1 & 0 \\ -s_\theta & 0 & c_\theta \end{bmatrix} \quad R_{z,\alpha} = \begin{bmatrix} c_\alpha & -s_\alpha & 0 \\ s_\alpha & c_\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Angle γ defines yaw (road crown), angle θ defines pitch (incline), angle α defines roll (the angle that the chair turns from the center-line of the road). For this case, the order of the transformations is pitch, roll, yaw. Hence, the above matrices are multiplied and transposed (to determine the inverse) in the specified order and the resulting relationship is given by

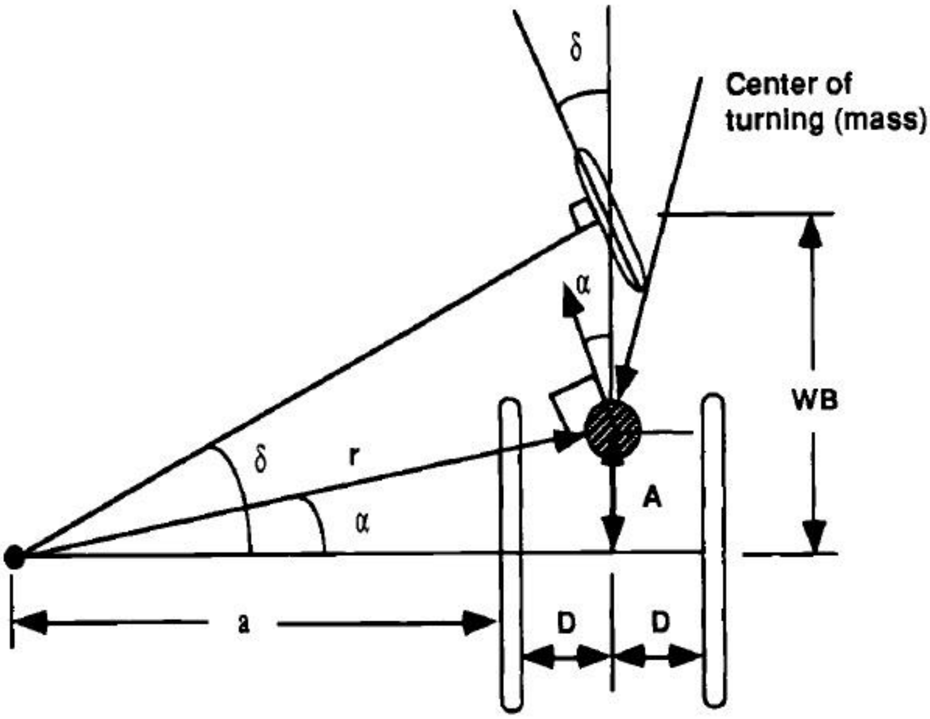


Figure 3. *Top view schematic diagram of turning geometry for stability analysis of steered wheelchairs and scooters.*

$$R_{\text{Chair}}^{\text{World}} = R_1^0 = \begin{bmatrix} c_\alpha c_\theta & s_\alpha c_\theta & -s_\theta \\ -c_\gamma s_\alpha + c_\alpha s_\gamma s_\theta & c_\gamma c_\alpha + s_\alpha s_\theta s_\gamma & s_\gamma c_\theta \\ s_\gamma s_\alpha + c_\alpha s_\theta c_\gamma & -s_\gamma c_\alpha + s_\alpha s_\theta c_\gamma & c_\gamma c_\theta \end{bmatrix}.$$

The projections, Lp and Dp, of the height of the center of gravity (L) of the wheelchair rider system and the distance (D) from the point of contact with the road of the outermost wheels to the center of gravity onto the road surface must be determined (figure 3).

The origins of the world coordinate system ($x_0y_0z_0$) and chair coordinate system ($x_1y_1z_1$) are located directly below the center of gravity in the plane of the bottom of the wheels. The vectors that define L and D in the chair coordinate system are given by

$$\boldsymbol{L}_1 = \begin{bmatrix} 0 \\ 0 \\ L \end{bmatrix} \quad \text{and} \quad \boldsymbol{D}_1 = \begin{bmatrix} 0 \\ D \\ 0 \end{bmatrix}.$$

The definitions for L and D in the world coordinate system with respect to the chair coordinate system are given

$$\boldsymbol{L}_0 = R_1^0 \boldsymbol{L}_1 = \begin{bmatrix} l_x \\ l_y \\ l_z \end{bmatrix} \quad \text{and} \quad \boldsymbol{D}_0 = R_1^0 \boldsymbol{D}_1 = \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix}.$$

The projections of L and D onto the x_0y_0-plane are the l_x, l_y and d_x, d_y components of $\boldsymbol{L}_0$ and $\boldsymbol{D}_0$

$$\boldsymbol{L}_p = \begin{bmatrix} l_x \\ l_y \end{bmatrix} \quad \text{and} \quad \boldsymbol{D}_p = \begin{bmatrix} d_x \\ d_y \end{bmatrix}.$$

The vectors describing L and D in the world coordinate frame can be calculated

$$\begin{bmatrix} l_x \\ l_y \\ l_z \end{bmatrix} = \begin{bmatrix} -s_\theta \\ s_\gamma c_\theta \\ c_\gamma c_\theta \end{bmatrix} L \quad \text{and} \quad \begin{bmatrix} d_x \\ d_y \\ d_z \end{bmatrix} = \begin{bmatrix} s_\alpha c_\theta \\ c_\gamma c_\alpha + s_\alpha s_\theta s_\gamma \\ s_\alpha s_\theta c_\gamma - s_\gamma c_\alpha \end{bmatrix} D.$$

The projections of L and D onto the x_0y_0-plane are given by l_x, l_y and d_x, d_y

$$\begin{bmatrix} l_x \\ l_y \end{bmatrix} = \begin{bmatrix} -s_\theta \\ s_\gamma c_\theta \end{bmatrix} L \quad \text{and} \quad \begin{bmatrix} d_x \\ d_y \end{bmatrix} = \begin{bmatrix} s_\alpha c_\theta \\ c_\gamma c_\alpha + s_\alpha s_\theta s_\gamma \end{bmatrix} D.$$

3.3.2. Fixed dynamic analysis of racing wheelchair roll stability

The matrix approaches derive as general fixed dynamic approach to wheelchair stability analysis. The component of the projection of the vector *D* (rotated) in the world coordinate frame which is orthogonal to z_o is required. By selecting the appropriate transformation matrix, this is simply the magnitude of the projection of *D* onto the $x_o y_o$-plane which is given by

$$D_p = D\sqrt{(s_\alpha c_\theta)^2 + \left(c_\gamma c_\alpha + s_\alpha s_\theta s_\gamma\right)^2}.$$

Equation can be represented in more compact form as a dot product

$$D_p = D\cos\tilde{\beta} \quad \text{where} \quad \tilde{\beta} = \cos^{-1}\left(\sqrt{(s_\alpha c_\theta)^2 + \left(c_\gamma c_\alpha + s_\alpha s_\theta s_\gamma\right)^2}\right).$$

To determine the roll stability of a wheelchair about its outermost wheels, the component of the vector (rotated) defining the height of the center of gravity in the chair frame which is orthogonal to the $\mathbf{z_o}$ axis and parallel to the vector ***D*** in the chair coordinate frame is required. This can readily be determined by using the fact that ***D*** and ***L*** are orthogonal in the chair coordinate frame. Hence

$$L_p = L\sin\tilde{\beta} = L\sin\left[\cos^{-1}\left(\sqrt{(s_\alpha c_\theta)^2 + \left(c_\gamma c_\alpha + s_\alpha s_\theta s_\gamma\right)^2}\right)\right].$$

The equations for the critical velocity for three- and four-wheeled wheelchair cases are given by

$$v_3 = \left[\frac{rg}{L}\left(\frac{D_p(WB_3 - A) - L_p WB_3}{WB_3}\right)\right]^{\frac{1}{2}}$$

$$v_4 = \left[\frac{rg}{L}\left(D_p - L_p\right)\right]^{\frac{1}{2}}.$$

In equations (v_3) and (v_4), r is the radius of the turn, g is the acceleration due to gravity, v is the forward velocity of the wheelchair/rider system, WB_3 is the wheelbase of the three-wheeled chair and A is the distance from the center of gravity along the center-line of the wheelchair to a line connecting the rear axles.

3.4. Impact Strength Tests

Impact strength tests are used to determine the strength of the wheelchair and its components under conditions that simulate typical usage. There are two basic types of tests performed to measure static strength: (1) static stress tests and (2) impact tests. ***Static stress*** testing is intended to determine whether the wheelchair can withstand the minimal static load prescribed. The minimal static load is representative of the static strength required of the wheelchair and its components under load levels that may occur during actual use. ***Impact tests*** are used to evaluate whether the wheelchair and its components are capable of withstanding occasional impact loading as may occur when bumping a curb or when being dropped.

3.4.2. Forward impact stability

Wheelchair users often cross door thresholds or hit small obstacles (e.g., sidewalk cracks, small stones) which may block or stall the front casters. When the front casters are stopped or substantially slowed, a moment is imparted on the wheelchair and rider which may cause the ride wheelchair to flip forwards. The component of the wheelchair user's velocity orthogonal to the door threshold or other obstacle is used in the analysis of forward impact stability.

Taking moments about the axles of the front caster, the moment of the impulsive force is zero and angular momentum is conserved (figure).

The equation for impulsive motion is given by $\boldsymbol{I_o\dot{\theta} = Mvy}$

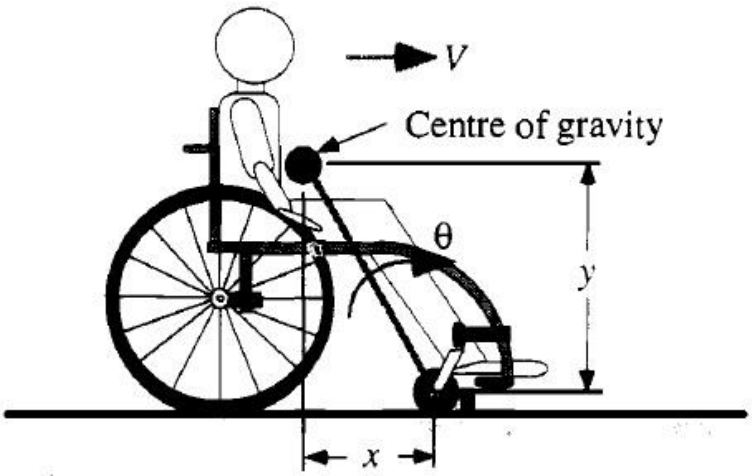


Figure *Simple sagittal-plane forward-roll stability model of a wheelchair and rider.*

where M is the total mass of wheelchair and rider, I_0 is the moment of inertia of the total mass about the axles of the front casters, v is the forward velocity of the wheelchair/rider when they first strike the obstacle, y is the height of center of gravity above the axles of the front wheels, and θ is the angular velocity of the wheelchair and rider.

For the wheelchair and rider to overturn, the center of gravity must be raised above the front axles of the wheelchair

$$\Delta h = \left(\sqrt{x^2 + y^2} - y\right)$$

where x is the horizontal location of the center of gravity from the axles of the front wheels.

If the wheelchair/rider are to overturn, the kinetic energy remaining after the impulse must be sufficient to lift the center of gravity for the system through the distance given above. This condition is given by

$$\tfrac{1}{2} I_0 \dot{\theta}^2 \geqslant Mg\Delta h = Mg\left(\sqrt{x^2 + y^2} - y\right)$$

where g is the acceleration due to gravity.

Equations can be combined to yield an equation that defines the critical velocity for flipping a wheelchair and rider about the front axles

$$v^2 \geqslant \frac{2gI_0}{My}\left(\sqrt{1 + \frac{x^2}{y^2}} - 1\right).$$

This means that for any particular wheelchair and rider, a minimum forward velocity required for overturning can be calculated.

3.5. Fatigue Strength Tests

Fatigue testing is used to determine the durability of wheelchairs and their components under a large number of low-level stresses that can have a cumulative effect during the life of the wheelchair, typically three to five years. During fatigue strength testing, wheelchairs must be equipped for normal use, and be thoroughly inspected prior to and after testing.

3.6. Test Dummies

There are four dummies used for wheelchair testing (25, 50, 75 and 100 kg). Dummies can be used for all tests where the wheelchair is to be loaded. The IS0 standard is based upon simple and inexpensive construction with mass distribution similar to a human

3.7. Power Wheelchair Range Testing

Energy consumption is measured over a distance of 1500 m while driving around a tennis court. The rolling surface is level in this case. The direction of rotation (i.e., direction was changed from clockwise to counter clockwise) is changed at 750 m. Wheelchairs are always driven in the forward direction.

$$range = \frac{\text{nominal battery capacity (amp} - \text{hour)} \times \text{speed traveled (kph)}}{\text{amperes consumed } (amp)}$$

The predicted range for the tennis court test at maximum speed ranges from a low of 23.6 km to a high of 57.7 km

3.7.2. Power Wheelchair Controller Performance

Power wheelchairs generally have a number of adjustable performance features that are dealer and/or user adjustable. Traditionally, powered wheelchairs have had a high/low switch for indoor and outdoor use. More recently wheelchairs have incorporated programmable controllers which can be tuned to meet an individual’s mobility needs. There is considerable discussion among the rehabilitation engineering community as to who should be able to tune a power-wheelchair controller. Several features can be programmed into microcontroller power wheelchairs. Maximum speed can be set within the wheelchair's capabilities. With some wheelchairs adjusting maximum speed also reduces maximum torque. However, for many this does not present a problem. Forward and lateral acceleration can be set to determine how rapidly the user can obtain maximum forward speed and how fast the user can turn the wheelchair. The forces and motor control required to operate input devices is important to safe and effective operation of a power wheelchair. Many wheelchair users have functional limitations which limit their ability to operate a joystick and/or other input devices.

Rehabilitation engineers should measure and report the forces required to actuate various operational control switches and input devices. A therapist or physician can provide assistance in determining the amount of force a user can exert for purposes of actuating control switches and input devices.

The mechanical performance of a wheelchair is subject to rolling friction, air drag, and internal friction of the wheelchair. Task load can be expressed as external power, or the energy per unit time that is required to maintain the speed of the wheelchair–user combination. With the help of a so-called "power balance," the forces and energy sources responsible can be systematically evaluated. ***The power balance for wheelchair propulsion can be expressed in the following equation:***

$$P_o = (F_{roll} + F_{air} + F_{int} + mg\sin\alpha + ma)\cdot v \ (W)$$

where

P_o is the external power output

a is the acceleration of the system

m is the mass of the wheelchair + user

α is the angle of slope or inclination

Apart from floor surface, rolling friction is essentially dependent on the characteristics of the wheels and tires; rolling resistance is lower for wheels with a larger radius and for harder tires. Rolling resistance can be expressed as the following equation:

$$F_{\text{roll}} = \eta_1(N_1 R_1^{-1}) + \eta_2(N_2 R_2^{-1})\ (N)$$

where

R_1 and R_2 are the radii of the front and rear wheels
N_1 and N_2 indicate the relative weight on those wheels
η_1, η_2 are the friction coefficients

The magnitude of the friction coefficients is related to the amount of deformation of tire and floor surface.

Air resistance The second important factor in the power balance equation is air resistance. In wheelchair racing this factor is by far the most important source of energy losses. Air resistance is dependent on the drag coefficient (C_d), frontal plane area (A), air density (∂), and velocity of the air flow relative to the object (v):

$$F_{\text{air}} = \frac{1}{2}\partial A C_d v^2\ (\text{N})$$

Internal friction

Energy losses within the wheelchair are caused by bearing friction around the wheel axles and in the wheel suspension of the castor wheels and possibly by the deformation of the frame in folding wheelchairs during the force exertion in the push phase. Bearing friction generally is very small, and given that the hubs have annular bearings and are well maintained and lubricated, this friction coefficient will not exceed 0.001.

An unknown aspect of internal energy dissipation is the loss of propulsion energy due to deformation of the frame elements. This will clearly be possible in folding wheelchairs, but has not been addressed empirically. The use of levers and cranks does introduce a chain, chain wheel and gearbox-related friction.