A Guideline for the Design of a Four-Wheeled Walker

by

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Abstract

More people use assistive technology devices to compensate for mobility impairments than for any other general type of impairment. Increasing numbers of people with mobility or balance problems use walkers with four wheels. Four-wheeled walkers are often outfitted with seats so that it is possible to travel longer distances with intermediate resting periods. The dangers of sitting on a parked walker are well known. Many physiotherapists actually tell walker users to park the walker against a wall to prevent injury in case the user forgot to apply the brakes, or the brakes fail.

To design a safer walker used for sitting, the demands placed on a walker must be measured. With these data, 3 modes of walker failure must be considered. The first mode is that the brakes may hold but the wheels slide along the ground. The second mode of failure occurs when the entire walker tips over. The third is brake failure in which the brakes cannot hold the wheels in place and they begin to roll. Mathematical models can be constructed that simulate how different walker designs will perform. By this process, design improvements can be made for existing walkers and future walker designs can also be proposed.

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I would like to thank both my supervisors for their time and effort invested in this project. I thank Dr. Cleghorn for accepting me as his student without hesitation and for his support and guidance. I would like to thank Dr. Fernie for teaching me how to approach problems with an open mind. Our time together has been invaluable.

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This paper is dedicated to my mother who has taught me how to enjoy life and my sister who I always enjoy it with.

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Nomenclature

a	Acceleration of walker (m/s^2)
A_Y	Shear force component of F acting at plate A (N)
A_Z	Normal force component of F measured at plate A (N)
b	Wheel base (cm)
B_Y	Shear force component of F acting at plate B (N)
B_Z	Normal force component of F measured at plate B (N)
c	Walker center of gravity measured horizontally from the braked wheels (cm)
C_Z	Normal force component of F measured at plate C (N)
d	Permissible sliding and rolling distance of either braked wheel
d_s	Incremental slide of the walker (cm)
d_t	Incremental rise of wheels of walker (cm)
F	Subject applied force (N)
F_B	Force acting at the braked wheels due to M_F (N)
F_c	Force acting at the center of gravity due to M (N)
F_F	Force acting at the free wheels due to M_B (N)
F_Y	Shear force component of F (N)
F_Z	Normal force component of F (N)
g	Acceleration due to gravity (m/s^2)
h	Permissible tipping height of the braked or free wheels (cm)
h_c	Linear displacement of the center of gravity (cm)
I	Moment of inertial of walker about free wheels ($\mathrm{kg} \cdot \mathrm{m}^2$)
j	Horizontal distance at the ground from the braked wheels to F for any s (cm)
k	Horizontal distance that F acts at height of the wheel axle from at the ground (cm)
M	Moment of walker about free wheels ($\mathrm{N} \cdot \mathrm{m}$)
M_B	Moment about the free wheels ($\mathrm{N} \cdot \mathrm{m}$)
M_F	Moment about the braked wheels ($\mathrm{N} \cdot \mathrm{m}$)
p	Horizontal distance at the ground from the braked wheels of the apparatus to the closest seat edge (cm)

P_A	Portion of F acting on plates A and B that is acting on plate A
P_B	Portion of F acting on plates A and B that is acting on plate B
q	Horizontal distance at ground from the braked wheels of the apparatus to F (cm)
r	Vertical distance that F acts at the height of the wheel axle (cm)
s	Walker seat position measured horizontally from the braked wheels to the closest seat edge (cm)
t	Small time increment (s)
v	Horizontal distance at ground from seat edge closest to braked wheels to F (cm)
W	Walker weight (N)
α	Angular acceleration of walker about free wheels ($^{\mathrm{rad}}/_{\mathrm{s}^2}$)
θ	Angular displacement (rad)
μ	Estimated static and dynamic coefficient of friction
μ_d	Dynamic coefficient of friction
μ_s	Static coefficient of friction

1. Introduction

1.1 Purpose

Growing numbers of elderly or disabled people with mobility and/or balance problems use walkers with the most rapidly growing market being walkers with four wheels. In general, four-wheeled walkers, also known as rollators, have two fixed wheels at the rear and two swiveling wheels at the front illustrated in Figure 1.1. The rear wheels are typically braked by a cable system similar to a bicycle. The similarity to shopping buggies and their more attractive colors seem to have increased their acceptability.

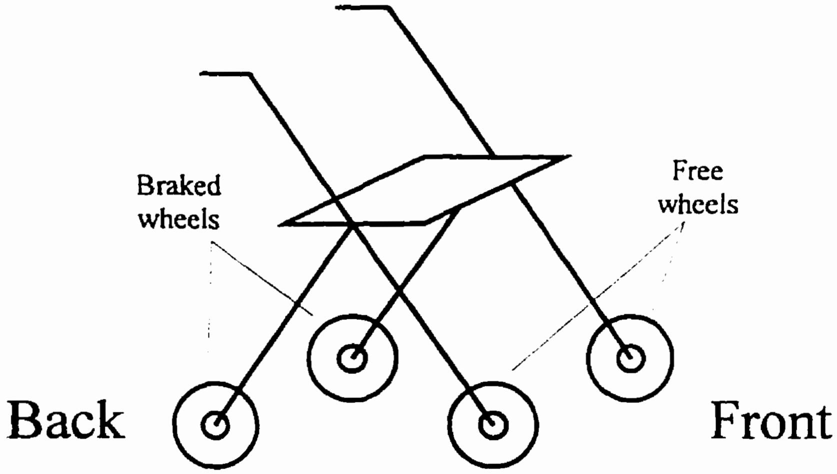


Figure 1.1 Diagram of typical four-wheeled walker

Four-wheeled walkers perform several functions in addition to increasing balance and stability. They are often outfitted with seats so that it is possible to travel longer distances with intermediate resting periods. Almost all walkers have adjustable handle heights and some have adjustable seat heights. The average seat height is 58 cm (23 in.) but it is useful to be able to vary that height by about 5 cm (2 in.) to accommodate taller and shorter adults. Usually walkers are also equipped with some kind of basket so they can be used effectively for shopping trips.

Walkers are one of the most widely used walking aids, yet little research has been done toward making them safer. To design a safer walker, the demands placed on a walker must be known. Only then can proper design parameters be created. Walker use can be divided into two categories. The first is the walker in motion where the user pushes the walker, and the second is a static walker with the wheels braked where the user sits on the walker. This study will focus on the comfort and safety of a walker being used for sitting.

Demands placed on a parked walker can be determined by duplicating a perfectly braked walker with absolute stability and having a walker user sit down and rise from it. Mathematical models can be constructed that will simulate how different walker configurations will perform. By this process, design improvements can be suggested for existing walkers and ideal walker designs can also be proposed. A safer walker design will not only reduce potential dangers for existing walker users, but will allow for a new population of walker users who would not consider walking with today's devices. Lowering barriers to movement and participation in exercise allows the use of walkers to contribute to increased levels of exercise and improved physical and mental health. Despite being critical information for the design of a walker, there is no published mechanical analysis of a walker being used for sitting.

1.2 Literature review

Walking frames have been in use for over one hundred years and help walking by aiding balance. About eight percent of Canadians have limitations in mobility [1] and more than 20,000 wheeled walkers are purchased in Canada each year [2]. More people use assistive technology devices to compensate for mobility impairments than for any other general type of impairment, with 1.7 million using walkers in the United States, which ranks second behind canes in numbers of users. Of this number, 1,307,000 or 77% are used by persons 65 years old and over [3].

The benefit of the manoeuverability of four-wheeled walkers is traded-off against stability. A recent study has identified the walker as the possible cause of at least 19,350 injuries annually in the United States [4] or 1.1% of the walker population. Physiotherapists routinely instruct walker users to park their walkers against a wall when being used for sitting in the case that the brakes are not applied or the walker slides.

Although studies have been performed with regard to the stability of walking frames [5,6,7], very little has been done regarding four-wheeled walker design. Improving the design will increase their value to those individuals with limited mobility and will also help to reduce walker-related accidents.

1.3 Modes of failure

When a walker user intends to sit on the walker, the brakes are applied and the user turns around and sits down (Figure 1.2). When the user is ready to walk again, he raises himself up, turns around, unlocks the brakes and continues walking. To examine the performance of a parked walker, three modes of failure should be considered. The first mode of failure occurs when the brakes hold, but the wheels may slide along the ground. The second mode results when the entire walker tips over. Finally, the third is brake failure in which the brakes cannot hold the wheels and they begin to roll.

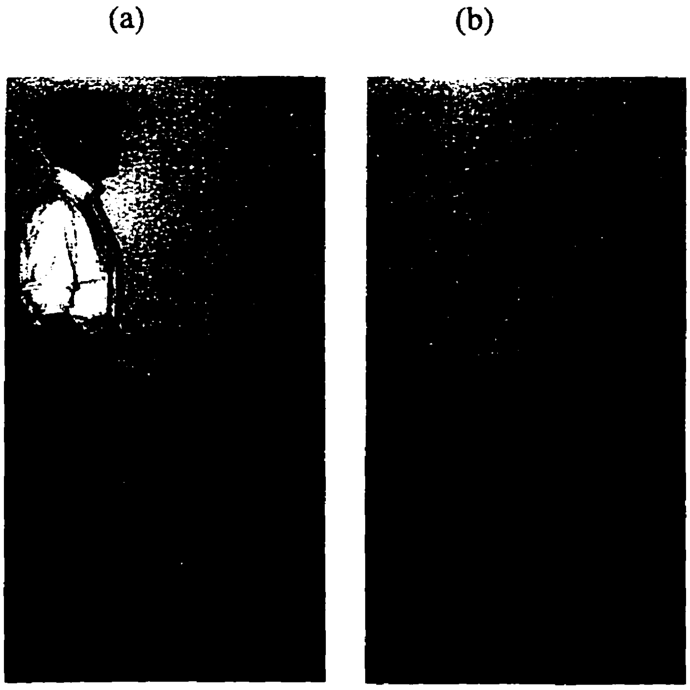


Figure 1.2 a) Walking with a walker b) Sitting on a walker

Sliding

When sitting and rising from a parked walker, the user applies a force F to the walker. A normal (vertical) force F_Z is transmitted through all four wheels and a shear (horizontal) force F_Y is transmitted through the braked wheels only (Figure 1.3). The total horizontal force acting through the braked wheels is comprised of a portion of the subject applied force and a portion of the walker weight. These horizontal forces need to be opposed by a coefficient of friction between the braked wheels and floor so that limited sliding will result. If the shear force divided by the total normal force at either of the braked wheels exceeds the coefficient of friction, sliding will result.

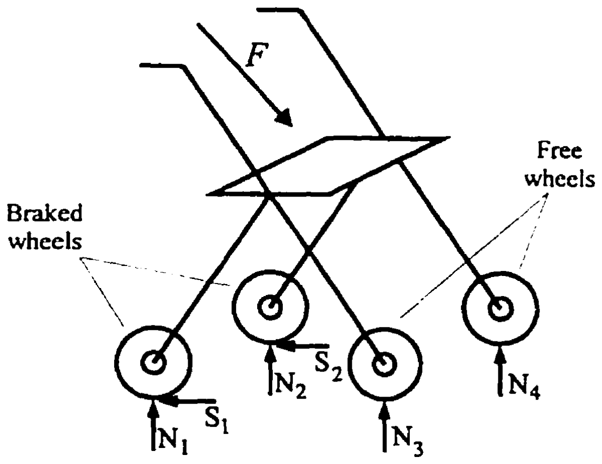


Figure 1.3 Distribution of subject applied force

Tipping

With the braked wheels locked, the walker can tip in two directions as seen in Figure 1.4. The first is counter-clockwise about the contact point of the braked wheels and the ground caused by a negative moment M_B, and the second is clockwise about the axle of the free wheels caused by a positive moment M_F. Tipping in the xz-plane (side-to-side) will be ignored because user applied forces are minimal in the x-direction. If the user force is applied behind or in front of the *wheel base* and creates enough of a moment to overcome the weight of the walker, tipping will result.

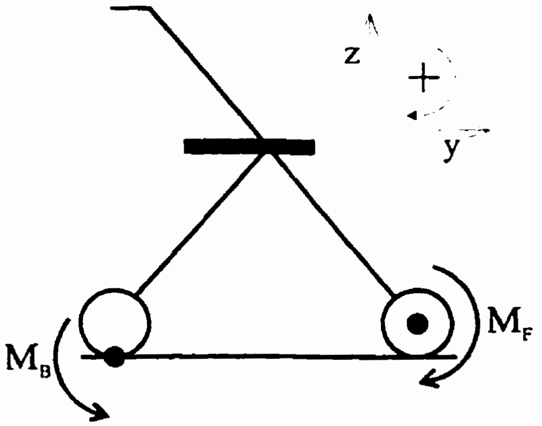


Figure 1.4 The two directions of tipping

Brake Failure

If there is enough normal force applied through the braked wheels to avoid sliding, brake failure will be dependent on the shear force component applied to the walker. If the shear force is high enough to overcome the gripping force of the brake on the tire, the brakes will fail and rolling will result.

2. Experimentation

2.1 Sitting and rising from a parked walker

2.1.1 Objective

As a walker user sits and rises from a parked walker, a force vector is applied to the walker which varies with time. This vector is transmitted through the walker wheels. As an ideal response to these forces, a walker should not slide along the ground or have any of the wheels come off the ground, ensuring stability. By securing the braked wheels of the walker to the ground with each wheel on a force plate, the user applied forces can be measured while simulating a perfectly braked walker.

2.1.2 Method

Apparatus

A commercially available walker was used to perform this experiment. By using a typical walker, the subjects would feel more comfortable and not alter their regular sitting pattern. Some alterations were made to the walker. The regular seat was removed and an adjustable seat was installed. The seat height could be placed in two positions. The low setting was 53 cm (21 in.) from the ground and the high setting was 63 cm (25 in.) from the ground (Figure 2.1). These are common high and low seat heights found on commercial walkers. For each seat height, there were three different horizontal seat positions for a total of six seat-handle configurations.

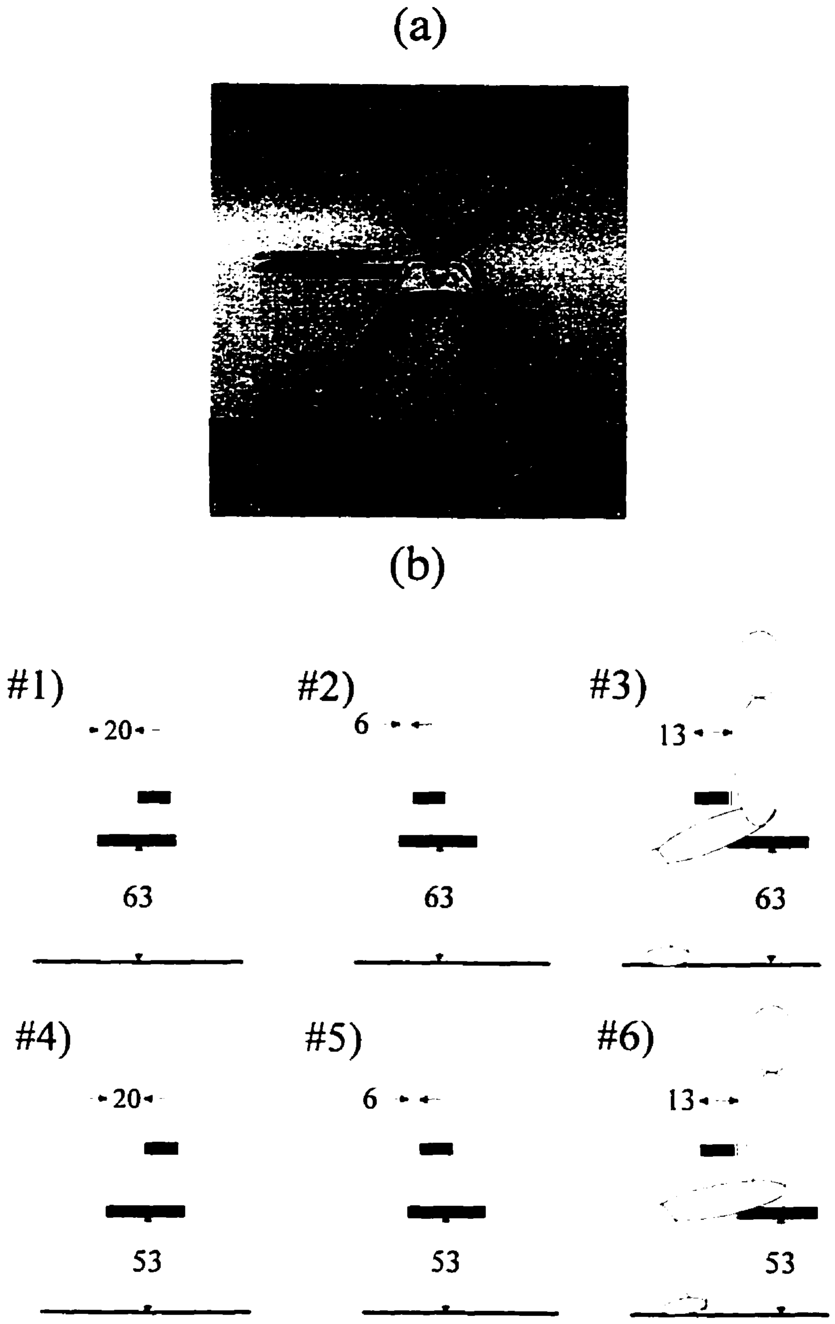


Figure 2.1 a) The apparatus set to configuration #4 b) Dimensions (cm) of each seat-handle configuration

The experiment was performed on a floor with three force plates in it seen outlined in Figure 2.2a. Two of these plates were AMTI OR6 platforms and the third was a Kistler 9281 platform. These plates act as scales that measure forces in all directions through load cells at each corner. A false floor was constructed above the force plates to allow the user to walk freely over the plates without contacting them (Figure 2.2b). This ensured that only the forces that the user applied through the walker would be recorded. Holes were cut in the floor to allow the legs of the walker to extend beyond the floor and contact the force plates.

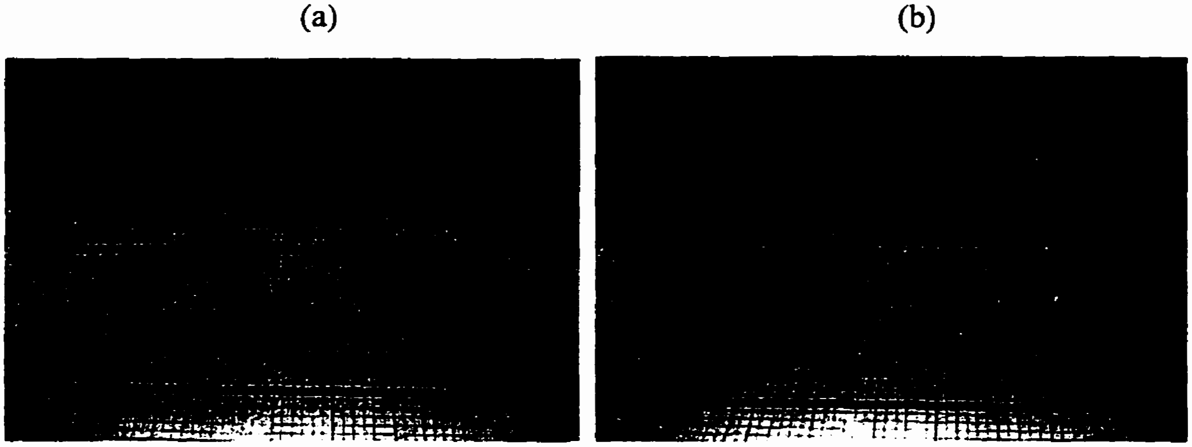


Figure 2.2 a) Outline of the three embedded force plates b) A false floor preventing feet from contacting the force plates

The back wheels of the walker were placed on V-shaped wedges of wood that were secured to force plates A and B (Figure 2.3). This construction replicated the conditions of ideally braked wheels that do not allow for any sliding or rolling. The free wheels both rested on a single force plate and were free to roll since there were no brakes on these wheels.

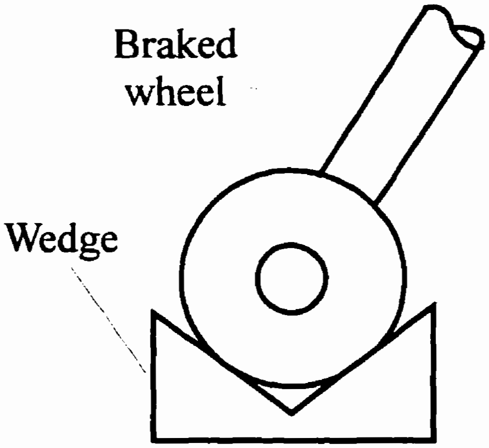


Figure 2.3 A wooden wedge was used to replicate an ideally braked wheel

In the unlikely case that additional stability was ever required by the subject, hand rails were always within grasping distance on both sides of the walker at all times. These were mounted to the floor independent of the walker. The cross beam of the walker was secured to the false floor by a chain with some slack to avoid the apparatus from tipping over during the trials. A picture of the completely assembled apparatus for a sample seat-handle configuration is shown in Figure 2.4.

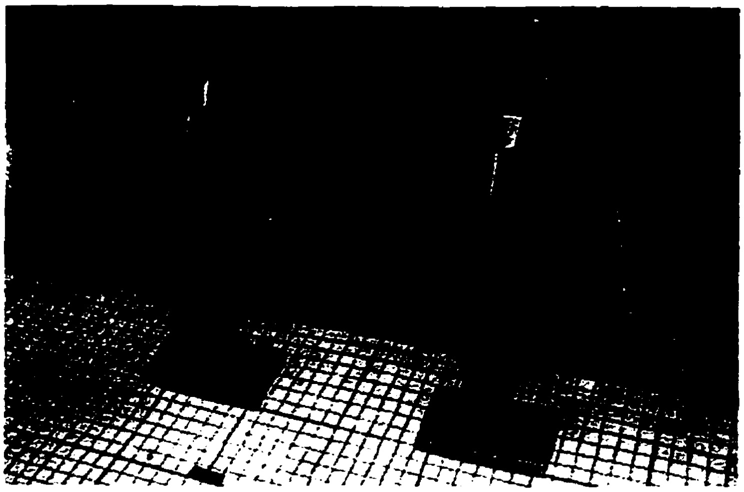


Figure 2.4 The completely assembled apparatus

Subject selection

The subjects were walker users who could understand the instructions given and were able to stand unassisted for at least one minute. Four male and three female subjects between the ages of 66 and 85 were tested (mean age = 74; SD = 6.7). Five of the subjects were recruited from the permanent residents wing at Sunnybrook hospital, one from the geriatric day hospital at Sunnybrook, and one from home. Subject characteristics are found in Table 2.1.

Subject #	Gender	Age	Height (cm)	Weight (kg)
1	Male	73	180	70
2	Male	75	179	77
3	Male	67	172	82
4	Female	74	168	60
5	Female	66	157	70
6	Male	85	174	82
7	Female	80	168	69

Table 2.1 Subject characteristics

Protocol

Prior to testing, each subject signed an informed consent statement in accordance with the ethics approval granted by the research ethics board at the Sunnybrook Health Science Center (Appendix A). The subjects were tested using the most appropriate one of three walker handle-height settings. The setting was determined by placing the handle at the height of the wrist with the arms relaxed. This allowed for a 15-25 degree bend at the elbow [8].

Subjects were asked to walk to the walker, seat themselves, count to two, and then raise themselves out of the walker and walk away. Thirty seconds were allotted to perform this task. Once complete, the subject either repeated the test or waited while the seat was set to a new position. The trial was then repeated. The adjustment of the seat took 3-5 minutes which allowed for the subject to rest. During this adjustment, the subject could sit on a stool beside the apparatus. Each of the six seat positions were tested twice for a total of 12 trials. The entire test took about one hour.

During the rest periods, the subjects were asked two questions. The first question was whether the walker would be more comfortable if the seat was higher, lower, or if they were comfortable the way it was. The second question asked if they would be more comfortable with the handles further toward the back or the front of the walker.

Data analysis

A "ringing" test was performed to determine the approximate sampling rate and filter cut-off frequency. The apparatus was struck with a hammer while sampling at an extreme rate of 500 Hz. A FFT revealed that the natural frequency distribution of the apparatus begins at about 8 Hz and peaks at 12 Hz. Based on these results, the tests were sampled at 50 Hz, more than four times the natural frequency of the apparatus. This would ensure that key data points and all important events would be collected. Filtering of the data would then have to be performed below the natural frequency. The cut-off frequency was set to 5 Hz.

The normal forces recorded were a combination of user applied forces and walker weight. The first ten data points of the recorded normal force for each trial were averaged for each force plate. These points record only the walker weight applied to the plates because the subject had not yet made contact with the walker. This force was then subtracted from the normal force component for every point in time to reveal the subject applied forces A_Z, B_Z, and C_Z for plates A, B, and C, respectively.

2.1.3 Results

A typical example of the forces recorded of someone sitting down and then standing for one trial is shown in Figure 2.5. Figures 2.5a and 2.5b show the normal and shear forces applied at each of the braked wheels, and Figure 2.5c shows the normal force applied at the two free wheels. The rise of the normal force is the subject being seated with the drop of the force resulting from the subject rising from the walker.

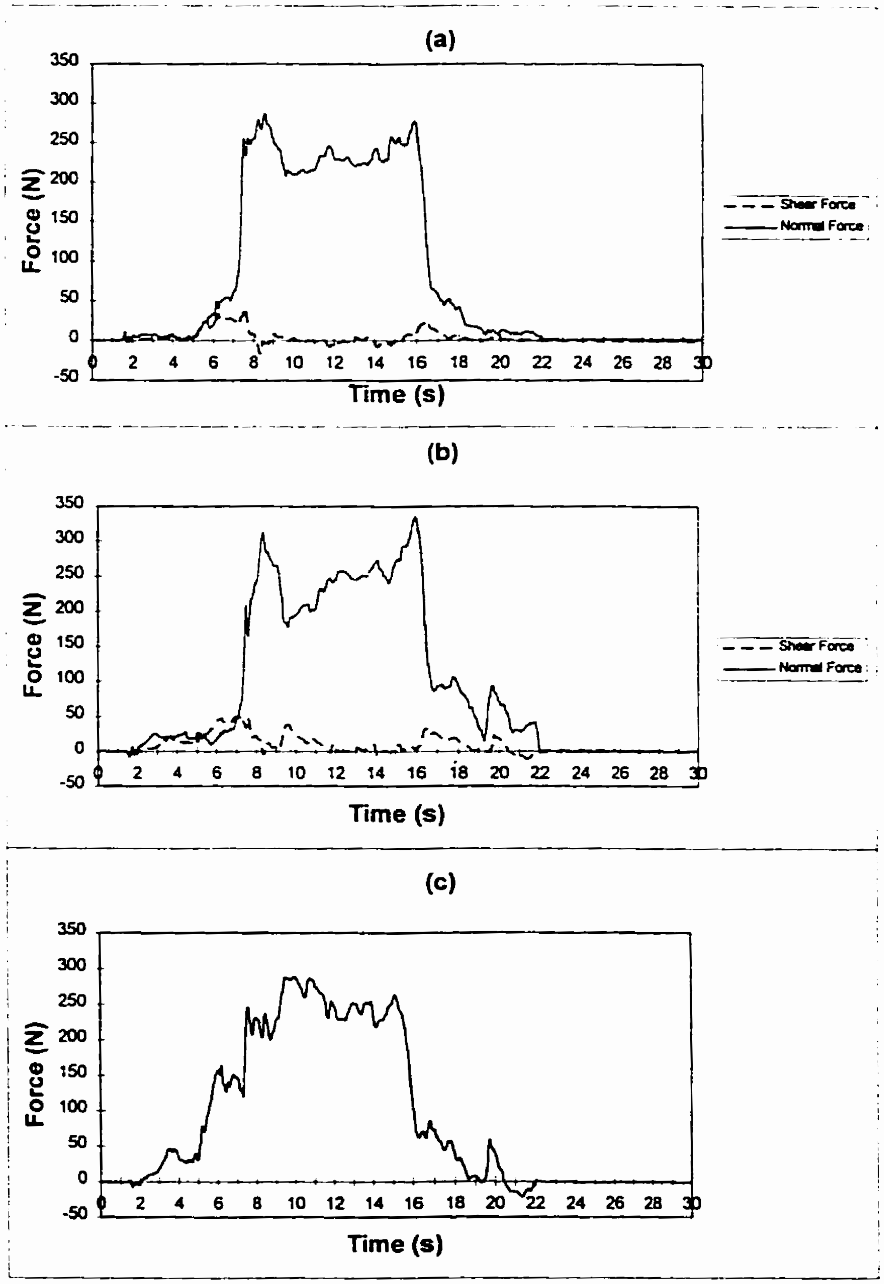


Figure 2.5 a), b) Normal and shear forces applied through plate A and B respectively c) Normal force applied through both free wheels

The responses to the questions regarding the comfort of the handle and the seat are summarized in Table 2.2. The seat-handle configurations that had the most "no change" answers with respect to both the seat height and handle position were considered to be the most comfortable. Based on this analysis, the most comfortable configuration has the most number of "no change" suggestions. This resulted in three grades of comfort with configuration #6 being the most comfortable, configuration #3, #4, and #5 being the second most comfortable and position #1 and #2 considered uncomfortable (see Figure 2.1). A chi-square test confirmed that these results were not random and should be considered as statistically significant.

Config.	Seat height			Handle position			Total
	Lower	No	Higher	Closer	No	Further	
1	6	1	0	4	2	1	3
2	7	0	0	3	2	1	2
3	4	3	0	0	6	1	9
4	0	6	1	5	2	0	8
5	0	4	2	2	4	0	8
6	0	7	0	1	6	0	13

Table 2.2 a) Responses to questions regarding seat and handle comfort

2.1.4 Discussion

During the experiment, the two heights and three horizontal seat locations were set. These different seat-handle configurations caused the subjects to apply different forces while sitting and rising from the walker. The position of the wheels to the seat and handles have no affect on the subject applied forces (for example, the apparatus could have been supported by one vertical pole from the floor to the bottom of the seat).

The most comfortable seat-handle configuration was #6. This configuration had the low seat setting with the handles as far behind the seat as possible (see Figure 2.1). Two of the three next most comfortable configurations had a low seat setting. The low seat allowed the user to sit straight down where most of the body weight could be supported by the walker while still allowing for the feet to rest comfortably on the ground. A higher seat often allowed the users to only perch themselves on the edge of the seat, or required sliding back in the seat to find a comfortable position. If the users wanted to sit comfortably on the higher seat, their feet were often off the ground resulting in an insecure sitting position. There is an advantage to only "perching" on the higher seat instead of sitting down fully on a lower seat. Leaning allows the user to stand easily instead of lifting the entire body up from a low seat.

The handle position further to the back of the walker was found to be more comfortable. This allowed users to guide themselves into the seat with extended arms. The handles were used to not only pull up, but to help to carry the body away from the seat. With a seat and handle position close to one another, the hands were brought into the sides with the elbows extending behind the user which can result in discomfort (Figure 2.6).

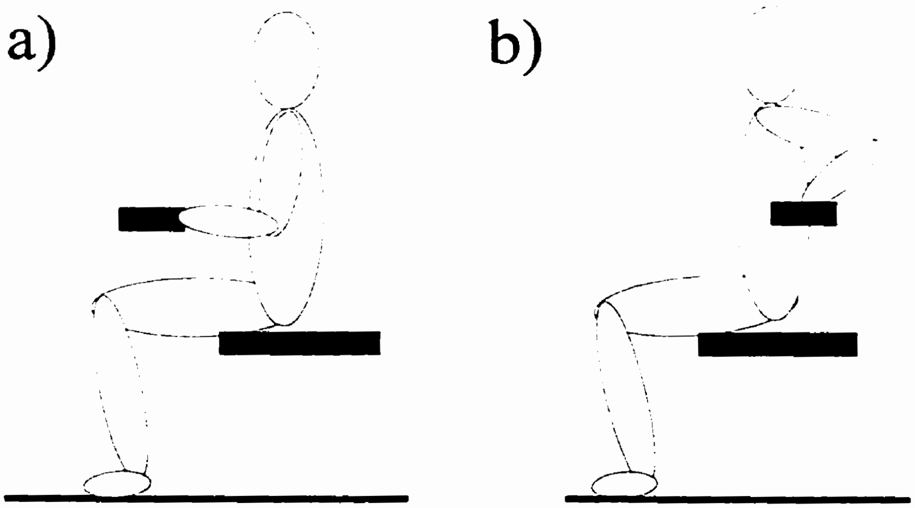


Figure 2.6 a) Comfortable and b) uncomfortable configurations

The most comfortable configuration of the seat and handle is an important design consideration, but the dangers of each configuration must be considered. Mathematical models were developed that analyze the dangers of the forces applied by the user for each configuration. This process, described in the following chapter, will determine which configurations are the safest to avoid each mode of failure. Comparing the results of the most comfortable configuration with the safest ones will then determine which configuration is the best.

2.2 Determination of existing coefficients of friction

2.2.1 Objective

Determination of the static and dynamic coefficients of friction that exist between different types of walker wheels and various floor materials is important to understanding the sliding mode of failure. By evaluating the properties of tires found on walkers interacting with common floor surfaces, a realistic range of coefficients of friction can be found.

2.2.2 Apparatus

A three-wheeled cart was constructed and can be seen in Figure 2.7. The two wheels at the front are free rolling, while the third is removable to be replaced by sample wheels used for testing. The test wheel rested on a force plate which recorded the normal and shear forces. Three wheels from different walkers were used during the tests. They were each bolted to the cart's center beam and then clamped securely to ensure that they would not roll but only slide.

A 6 kg weight was used to apply vertical loads to the test wheel. Three different materials were placed on the force plate to simulate various floor surfaces. Samples of carpet, ceramic tile, and vinyl flooring were used.

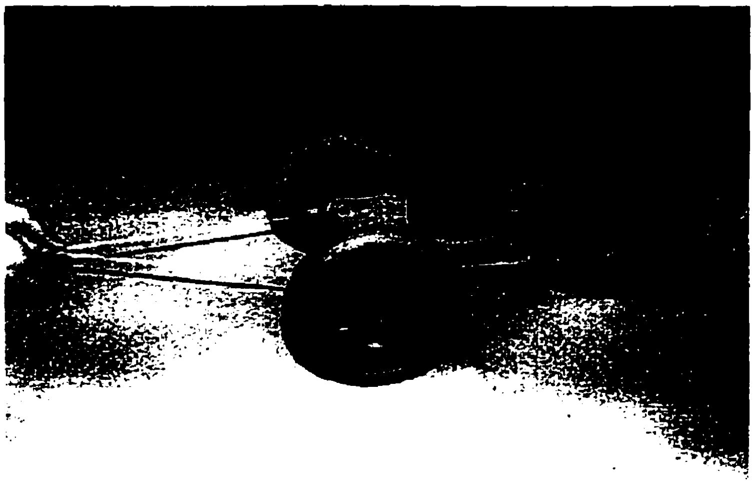


Figure 2.7 Friction measuring cart

2.2.3 Procedure

For each test, the floor material was attached to the force plate. The clamped test wheel of the cart was placed on the floor material with the other two wheels off the force plate able to roll in the direction of the applied shear force. The weight was then placed in one of two positions: 1. close to the test wheel, or 2. close to the free wheels. With the force plate recording the forces and making sure to keep the rope level with the ground and in the direction of rolling, an increasing shear force was slowly applied by pulling on the rope until sliding was observed. Once movement was detected, the horizontal force was gently reduced until movement stopped. The values obtained for each weight position were then averaged.

The test was performed for each wheel using all three floor materials, and both weight positions for each material. In total, 18 tests were performed, comprised of two tests per material, three materials per wheel, and three wheels.

2.2.4 Results

The data for one wheel are shown in Figure 2.8a. This graph shows the normal and shear forces acting through the test wheel. The units of the "distance" curve are irrelevant. Only the characteristics of this curve are important. The shear force divided by the horizontal force is shown in Figure 2.8b. This represents the coefficient of friction between the floor material and the wheel.

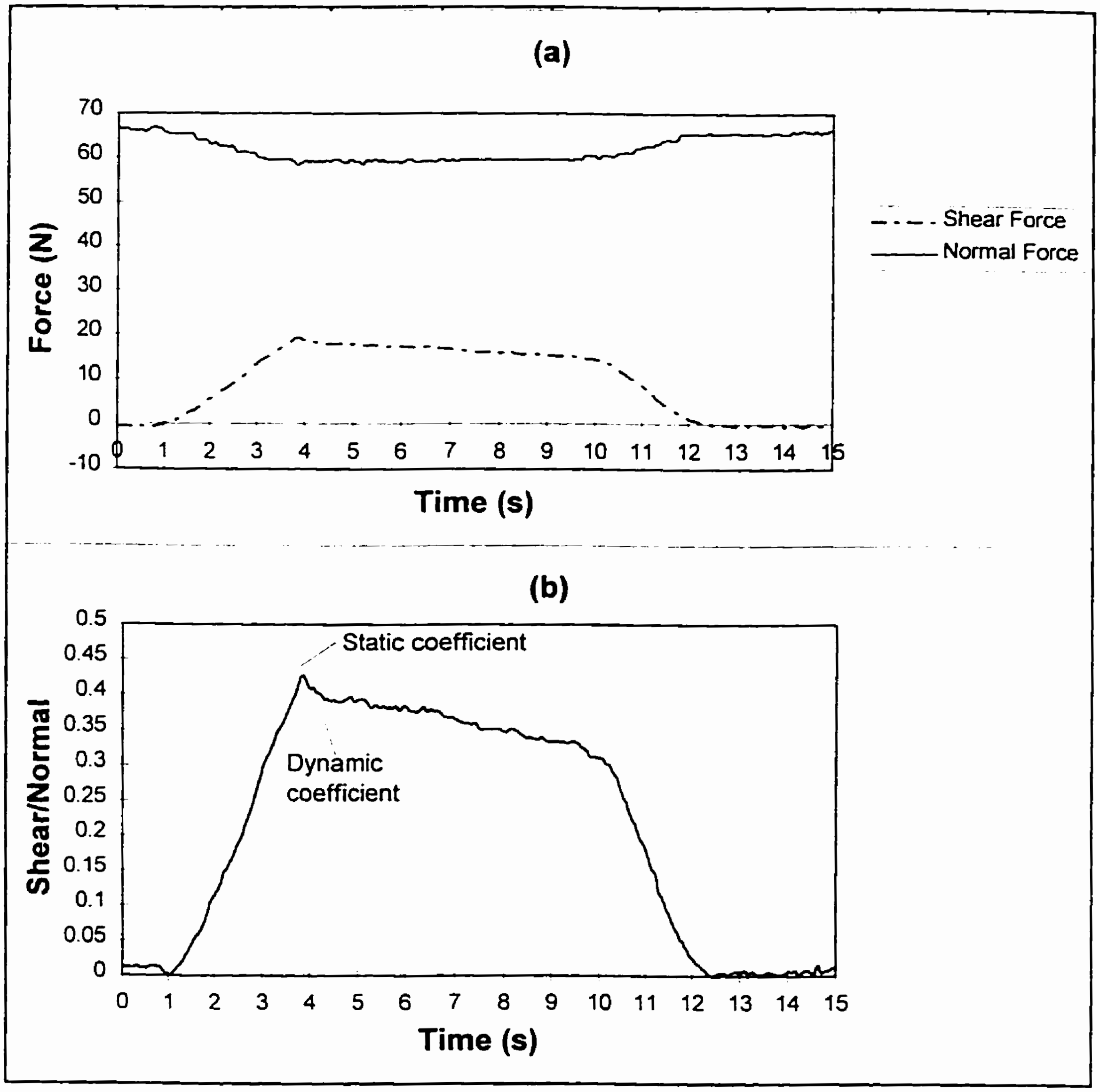


Figure 2.8 a) Normal and shear forces with distance slid b) Shear divided by normal force to determine coefficient

The static coefficient of friction (μ_s) is the shear/normal ratio at the point in time at which sliding begins. The dynamic coefficient of friction (μ_d), is the shear/normal ratio once the body is moving and is smaller than (μ_s). To find (μ_s) from the data, the point in time where the distance begins to change must be isolated. The shear/normal forces for that same point will yield (μ_s). The shear/normal ratio soon after movement has begun represents (μ_d). This value is more difficult to pinpoint and could only be isolated in three trials. The coefficients of friction of the three wheels on the various floor materials are given in Table 2.3.

	Ceramic tile		Carpet		Vinyl flooring	
	μ_s	μ_d	μ_s	μ_d	μ_s	μ_d
Tire #1	**0.44**	**0.40**	**0.45**	—	**0.55**	—
Tire #2	**0.50**	**0.45**	**0.75**	—	**0.46**	**0.44**
Tire #3	**0.65**	—	**1.0**	—	**0.80**	—

Table 2.3 Static and dynamic coefficients of friction of three walker wheels

2.2.5 Discussion

The dynamic coefficient of friction value was taken at the point closest to the static value. The common characteristic of dynamic coefficient of friction curve having a negative slope was ignored and the highest value was recorded. The test showed that the dynamic coefficient of friction is only 0.05 less than the static coefficient for the worst case. Coefficient of friction tables revealed that rubber tires on dry pavement have a dynamic coefficient of friction up to 0.05 less that static [9]. Since the difference between the μ_d and μ_s values corresponded to the literature and were about 10% at most, the static and dynamic coefficients of friction can be considered as the same value, μ.

The values of the dynamic and static coefficients of friction obtained from this experiment are used as guidelines when evaluating the performance of a parked walker. The coefficients can then tell us at what point the user applied forces surpass these values and the users put themselves in danger. The tests were performed using typical walker wheels on common floor surfaces. By using the lowest coefficients obtained for the selected tire over commonly encountered floor materials, safe designs can be created.

3. Development of design guidelines

3.1 Introduction

Nine variables involved in designing a walker for safe transfer between sitting and standing will be considered as seen in Figure 3.1:

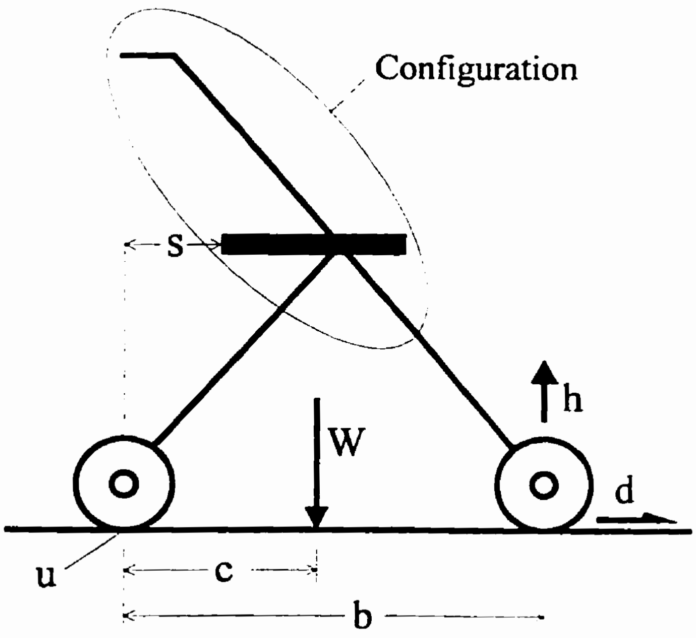


Figure 3.1 Walker design variables

1. *Wheel base*

The wheel base (*b*), measured in centimetres, acts as the support of the walker.

2. *Walker mass*

The walker weight (*W*), measured in Newton's, or the walker mass ($^{W}\!/_{g}$), measured in kilograms, acts as an anchor for the walker.

3. *Centre of gravity*

A walker may be very heavy but if the centre of gravity (c) is improperly placed, it may be less stable than a lighter walker with an appropriate centre of gravity. The position of the centre of gravity is measured along the y-axis from the braked wheel.

4. *Coefficient of friction*

Sliding begins once the static coefficient of friction is exceeded. The walker will keep moving until the applied forces fall below the dynamic coefficient of friction. For this analysis, since the static and dynamic coefficients were found in the above experiment to be within 0.05 of each other (10% in the most extreme case), μ will represent one coefficient of friction that will approximate both values.

5. *Configuration*

The distribution of forces applied by the user will be affected by the seat height and relative handle location. The structure of the frame and accompanying wheel locations have no affect on the forces applied by the user. Six seat-handle configurations were tested as described in the experimentation. Comfort and safety are the two issues that must be considered when determining the appropriate configuration. Certain configurations may be more comfortable, yet may transmit combinations of forces that create hazardous sitting situations, while some configurations can be very safe but extremely uncomfortable. The position of the seat-handle configuration will be measured with respect to the rest of the walker by the back edge of the seat.

6. *Seat position*

The configuration and accompanying user applied forces are independent of the wheel base. The seat can be placed anywhere over the wheels without affecting how the user will sit, but the position will affect how safely the user will sit. To relate the configuration to a given wheel base, its seat position (s) is measured from the braked wheels to the edge of the seat closest to those wheels.

7. Slide distance

Although sliding is a mode of failure of a parked walker, very short slides will go unnoticed by the user. The maximum sliding distance permitted (*d*) will be held constant at 5 cm (2 in.) for the remainder of this analysis. This was found to be an unnoticeable movement and allows for realistic design parameters while maintaining stability for the user.

8. Tipping height

Tipping is a mode of failure, yet small rises of the wheels from the ground will go unnoticed by the user. A permissible tip (*h*) resulting in the wheels rising only 2 cm (0.8 in.) off the ground was selected since the movement was found to be barely noticeable and this value allows for more flexibility in the design.

9. Brake shear

The brake at each wheel must withstand a certain amount of shear to avoid brake failure which results in rolling. This required brake shear must only allow for a total of 5 cm (2 in.) of rolling, the same as the permissible slide distance. This variable is not indicated in Figure 3.1.

3.2 Theory

3.2.1 Sliding

As a user sits down and rises from the walker, the force vector applied to the walker varies with each point in time. The applied force is composed of a normal (vertical) and shear (horizontal) component with the normal force distributed among all four wheels and the shear component among the two braked wheels (see Figure 1.3). Considering the sliding of a braked wheel, the normal or shear force curves alone are of no use (see Figure 2.5). Only the shear/normal ratio can indicate when to expect sliding. Figure 3.2 represents the shear/normal ratio for one braked wheel of an entire 30 second trial. The significant rise from five to seven seconds indicates when the subject sits down, and the rise from 16 to 20 seconds indicates when the subject rises from the walker.

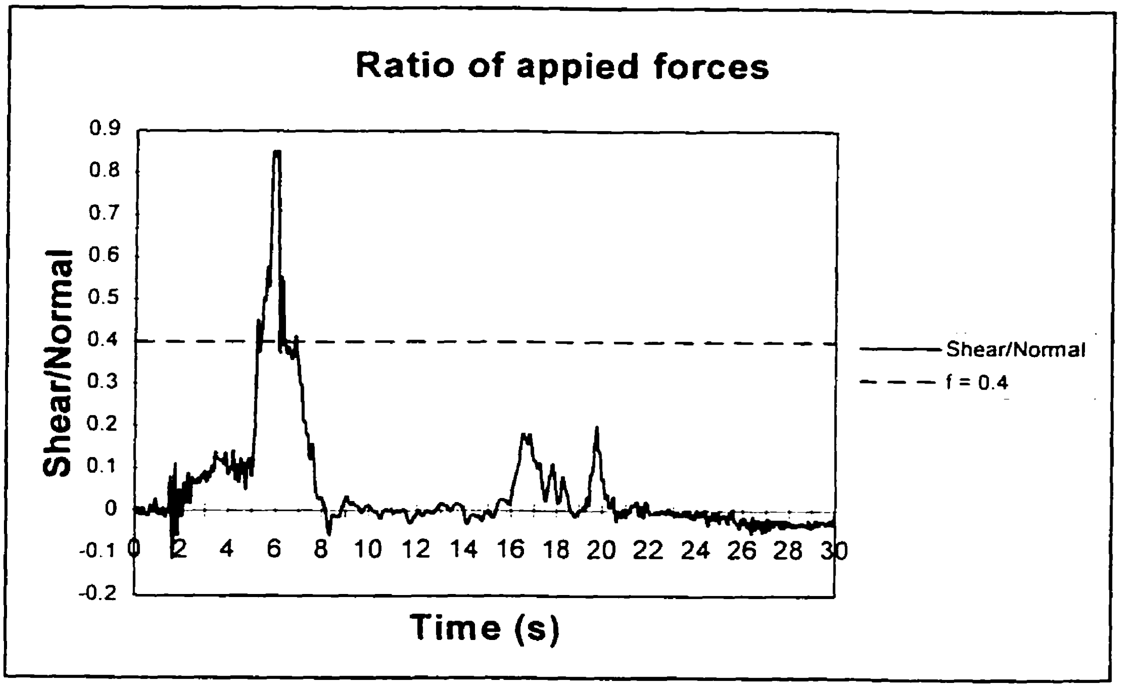


Figure 3.2 Shear/Normal ratio for one braked wheel

Sliding will begin once the shear/normal ratio at a braked wheel exceeds the static *coefficient of friction* between the wheel and the ground. The walker will keep sliding until the ratio falls below the *coefficient of friction*. The horizontal line in Figure 3.2 represents an example *coefficient of friction* $\mu = 0.4$ with the peaks above this line implying sliding. By increasing the normal force over the braked wheels, the entire curve can be lowered to reduce the sliding distance. Seven of the nine design variables can be adjusted to reduce sliding:

Walker mass and *centre of gravity*

There are two sources of normal forces acting on the braked wheels. The first is the applied user force and the second is the *walker mass*. The higher the *walker mass*, the greater the normal force will be acting through the wheels. The closer the *centre of gravity* is to the braked wheels, a greater portion of *walker mass* will act through them and the less the walker will tend to slide.

Coefficient of friction

Sliding will begin once the shear/normal ratio at a braked wheel exceeds the *coefficient of friction* between the wheel and the ground. The walker will keep sliding until the ratio falls below the *coefficient of friction* implying that the higher *the coefficient of friction* is of the walker wheels, the more stable the walker will be.

Seat Position

As mentioned above, the forces applied by the subject are dependent on the *configuration* only and are independent of the location of the wheels. The distribution of the user applied forces among the wheels is affected by the *seat position*. Figure 3.3 shows the applied force vector for one point in time for a sample *configuration*. During the sliding analysis, the vector's position will be calculated at the ground.

With respect to the shear force component, there is no distribution among the braked and free wheels because the free wheels do not help to resist the shear. The braked wheels will always have the entire shear force acting on them independent of the *wheel base* and *seat position.*

The normal force component of the vector (F_Z), is supported by both the free and braked wheels. The closer the force acts to one of the wheels, the greater the portion of the total normal force that wheel will support. Based on this principle, the *seat position* is very important in calculating how much normal force is acting through the braked wheels. A *seat position* closer to the back of the walker will result in much more of the subject applied normal force through the braked wheels than *a seat position* towards the front (see Figure 1.1 for front and back reference). The total normal force acting through a braked wheel is therefore a fraction of the total applied user force plus the share of the *walker mass* that the braked wheel supports.

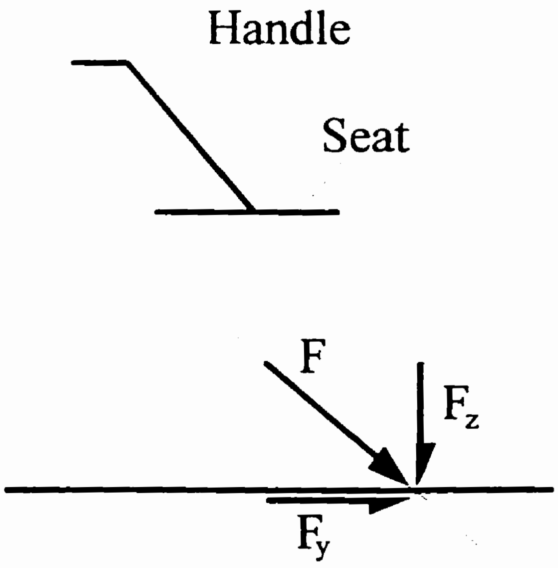


Figure 3.3 Applied force vector for one point in time

Wheel base

The location of the forces applied by the user is measured from the back edge of the seat. For a fixed *seat position* to *wheel base* ratio, adjustment of the *wheel base* can alter the amount of force distributed among the wheels. For a *seat position* of 50% of a small *wheel base* (Figure 3.4a), the applied normal force is supported more on the free wheels. By doubling the *wheel base* (Figure 3.4b), the *seat position* to *wheel base* ratio remains constant, but more of the force is supported by the braked wheels.

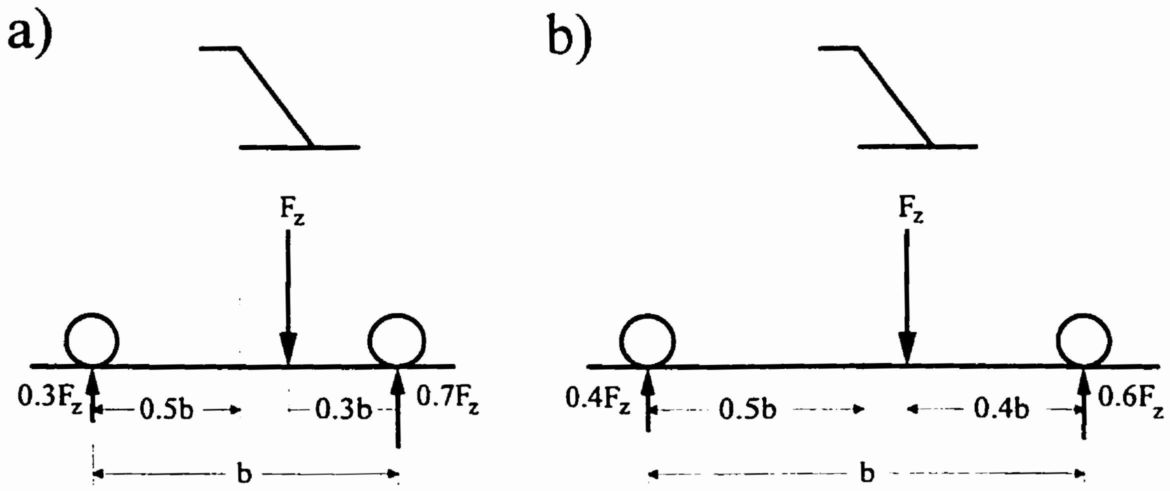


Figure 3.4 Distribution of applied force for a a) short wheel base, and b) long wheel base

Configuration

Varying the seat height and relative handle position will cause the user to apply different forces. Certain *configurations* will be less prone to sliding.

Slide distance

To avoid *any* sliding, as mentioned above, the total normal force on the braked wheels must be increased so the spikes on the shear/normal graph (Figure 3.2) lie below the *coefficient of friction*. Sliding will happen over the entire range that exceeds the *coefficient of friction*, yet the amount of sliding may not be detected by the user. A slide of a few centimeters may be as safe as a perfectly static walker, yet the differences in design requirements of a walker that allows no sliding and one that allows for very little sliding are significant. If absolutely no sliding movement was permitted, then the design would be too conservative (i.e. the walker would be unnecessarily heavy). Through observation of walker users and postural stability data, a 5 cm (2 in.) slip was determined to be the *slide distance* limit.

3.2.2 Tipping

The walker can tip in two possible directions as indicated in Figure 1.4. One way is about the contact point of the braked wheels and the ground, and the other is about the free wheels' axles. Tipping about the free wheels would begin with no weight on the braked wheels. In this case, sliding would result before the walker would tip, however, we will consider the case where movement of the free wheels is restricted (e.g. soft grass or an obstacle).

As the subject sits or stands, if at any point in time the applied force vector and *walker weight* combine for a resultant force outside of the *wheel base*, the wheels will begin to rise off the ground. With a positive moment in the clockwise direction, for the braked wheels, any time the moment is negative the free wheels will begin to rise from the ground. Similarly for the free wheels, any time the moment is positive, the braked wheels will begin to rise.

The only opposing force that will help to maintain the stability of the walker is the *walker weight*. As long as the resultant of the combined *walker weight* (*W*) and applied force (*F*) are contained within the *wheel base*, tipping will be avoided. Five of the design variables affect tipping:

Seat position

The *seat position* determines where the user applied forces are acting relative to the seat. If the *seat position* is very close to either the free or braked wheels, the applied forces lie far outside the *wheel base* causing higher tipping moments.

Wheel base

A larger *wheel base* reduces the tipping moment caused by the forces applied outside of the *wheel base* by shortening the distances that they are acting from the wheels.

Walker mass

A higher *walker mass* creates a greater inward moment which helps to stabilize the walker.

Centre of gravity

The *centre of gravity* of the walker will control how great a stabilizing moment the *walker weight* will cause about the wheels.

Configuration

Varying the seat height and relative handle position will cause different user applied forces. Certain *configurations* will be less prone to tipping.

3.2.3 Brake failure

Brake failure can only occur when there is enough normal force acting through the braked wheels to avoid sliding. Under this condition, only the applied shear and *walker weight* will influence brake failure. If the shear applied to either of the braked wheels exceeds the grip of the brake on the tire, the wheels will roll. As in sliding, small movements of the walker will go unnoticed by the user. Figure 3.5 shows the user applied shear through one braked wheel over an entire trial. The horizontal line represents the shear that the brake can withstand without allowing rolling. The portion of the curve above this line indicates rolling. The shear that allows less than 5 cm (2 in.) of rolling must be found to restrict the wheels to minimal rolling and avoid dangerous brake failure.

Since all shear forces that act through the walker are distributed through the braked wheels only, design variables that will affect brake failure are the seat-handle *configuration* and the *walker mass*. As the *walker mass* increases, there is a greater load to accelerate resulting in less movement.

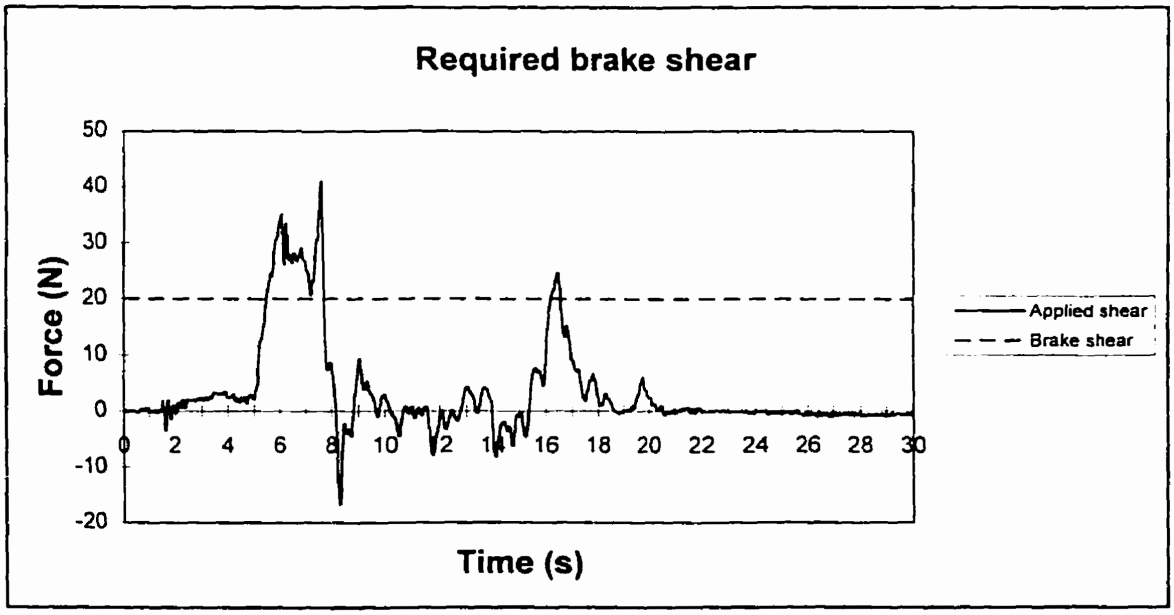


Figure 3.5 User applied shear force and brake shear setting

3.3 Calculations

3.3.1 Sliding

Finding the location of the user applied force vector:

The normal forces due to the walker's own weight have been subtracted from the total normal forces measured on each force plate as the first step in signal processing. The normal forces measured by the three force plates (Figure 3.6) total the normal applied force:

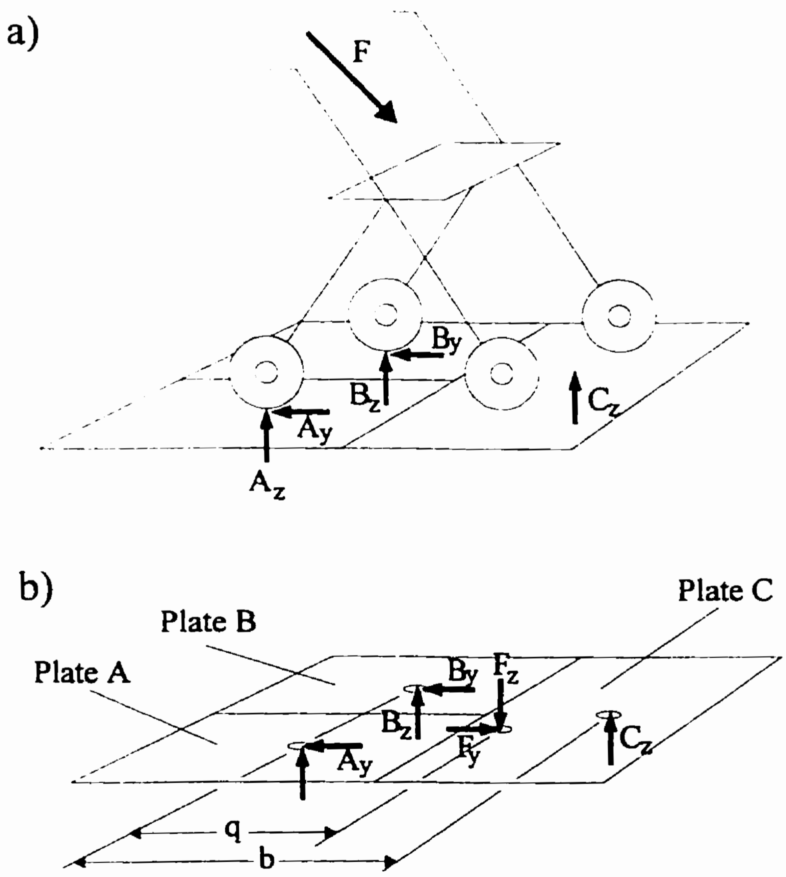


Figure 3.6 a) Walker on force plates b) The location and magnitude of the applied force F can be determined by the forces measured by the force plates

$$Fz = Az + Bz + Cz$$

where F_Z is the subject applied normal force and A_Z, B_Z, C_Z are the subject applied normal forces for plates A, B and C, respectively. Taking moments about the point of contact of the braked wheels and the floor:

$$q = \frac{Cz \cdot b}{Fz}$$

where q is the horizontal distance (cm) from the braked wheel to the force vector and b is the *wheel base* (cm).

q is measured along the y-axis from the contact point of the braked wheels and floor which is still dependent on the arbitrary *wheel base* of the apparatus. The user will apply the same forces independent of the *wheel base* or wheel positions. The force vector must be related to the seat and handles only so that the *configuration* can be positioned over any *wheel base* and *seat position.*

As indicated in (Figure 3.7a), (p) is the horizontal distance from the braked wheels to the back edge of the seat *of the apparatus*, and (q) is the horizontal distance from the braked wheels *of the apparatus* to the force vector. ($v = q - p$) then becomes the horizontal seat-to-force distance independent of the wheels and therefore independent of the apparatus. With the apparatus measurements no longer of consequence, the force location can be related to any given *wheel base.* The *seat location* (s) for any given walker design (not to be confused with the seat location of the apparatus (p)) is added to (v) to yield the horizontal distance of the applied force from the braked wheels ($s + v = j$) (not to be confused with the horizontal distance of the applied force from the braked wheels of the apparatus, (q)) (Figure 3.7b).

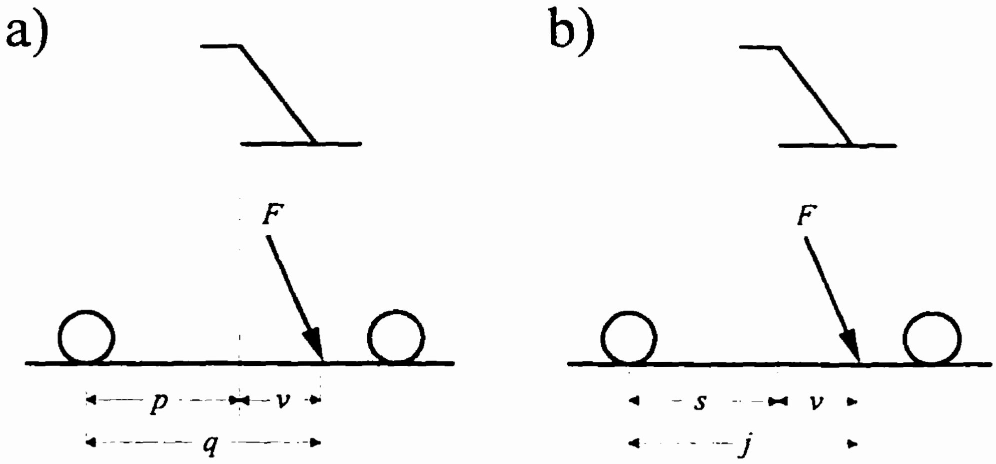


Figure 3.7 Measuring F from the braked wheels of a) the apparatus b) general designs

Finding the normal force acting at each braked wheel for each point in time:

The normal and shear force components of the applied user force acting at (*j*) are now known. With the *walker mass* and *centre of gravity* also known, the total normal force acting at each braked wheel can be calculated. At this point, two assumptions are made:

Assumption #1	The *walker mass* is equally distributed about the sagittal (*yz*) plane
Assumption #2	All wheels have even contact with the ground

Although the *walker mass* will be equally distributed, the subject applied force is not. The distribution of the total applied force acting through the braked wheels between plates A and B, P_A and P_B respectively, can be found from A_Z and B_Z:

$$P_A = \frac{Az}{Az + Bz}$$

$$P_B = \frac{Bz}{Az + Bz}$$

The total subject applied force (*F*) can act beyond the *wheel base* and have three affects:

1. The subject applied force may not cause a great enough moment to lift either the free or braked wheels. The normal forces at the braked wheels will only be a fraction of the total user applied force. A moment calculation is performed about the point of contact between the ground and the free wheels to determine the normal acting on each braked wheel (A_Z and B_Z).

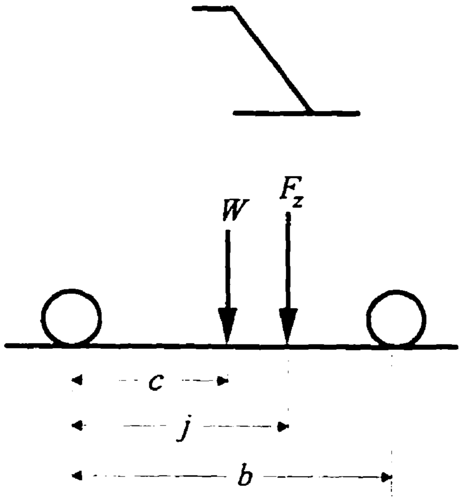


Figure 3.8 Calculating A_Z

Using plate A as an example (Figure 3.8), the moment caused by A_Z (which is unknown) is ($Az \cdot b$). Half of the *walker mass* will be considered as acting on each side of the *yz*-plane, as mentioned above. The weight applied by each half of the walker ($W/2$) will be acting at the location of the *centre of gravity* (*c*). This is measured as a percentage of the *wheel base* from the braked wheels. The distance to the free wheels will then be $[b \cdot (1-c)]$. The normal component of the user applied force (Fz) is multiplied by P_A to find the amount of this force acting on the side of the walker with plate A. This force can then be multiplied by its distance to the free wheels, ($b - j$). The overall moment equation becomes:

$$Az \cdot b - W/2 \cdot b \cdot (1-c) - P_A \cdot Fz \cdot (b-j) = 0$$

Isolating for the unknown force at the braked wheel A_Z:

$$Az = \frac{{}^{W}\!/_{2} \cdot b \cdot (1 - c) + P_A \cdot Fz \cdot (b - j)}{b}$$

2. If the force creates enough negative moment when acting to the left of the braked wheels to lift the free wheels, the normal force on the braked wheels is the sum of the *walker weight* and the subject applied force for that moment in time:

$$Az = P_A \cdot Fz + \left({}^{W}\!/_{2}\right)$$

3. If the force creates enough positive moment when acting to the right of the free wheels to lift the braked wheels, obviously the normal force on the braked wheels is zero.

Incorporating small but harmless slips:

Once the applied forces exceed the *coefficient of friction*, the *slide distance* must be found. The braked walker wheel applies a normal force to the ground equal to the vertical load that it bears. At this point another assumption is made:

Assumption #3 Causing one wheel to slide requires pushing half of the walker mass

This model can be seen in Figure 3.9. It is not known if any additional mass is coupled to the walker while the user is applying the force.

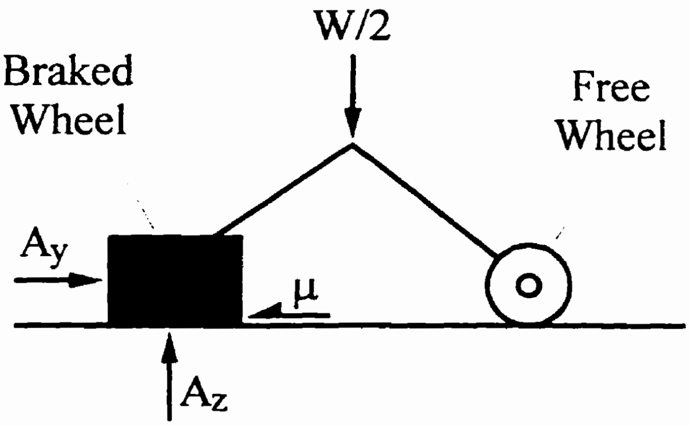


Figure 3.9 Model to simulate sliding of braked wheel

The worst case is therefore considered in which none of the subject's mass is applied to the walker. An opposing frictional force μ, acting in the direction opposite to the applied shear force will be acting at all times equal to ($\mu \cdot Az$). The *slide distance* for the wheel contacting the ground can be found as follows:

$$Ay = \mu \cdot Az + {}^{W}\!/_{2g} \cdot a$$

where a is the acceleration of the wheel. All variables are known except for this acceleration. Isolating for the acceleration:

$$a = \frac{Ay - \mu \cdot Az}{{}^{W}\!/_{2g}}$$

For uniform acceleration ($a = const.$):

$$d_s = V_o \cdot t + \tfrac{1}{2}at^2$$

where d_s is an incremental distance slid over a small interval of time (t). Assuming $V_o = 0$ over this short time span with constant acceleration:

$$d_s = \tfrac{1}{2}at^2$$

For the case of the wheel not contacting the ground ($F_Z = 0$):

$$F_Y = {}^{W}\!/_{2g} \cdot a$$

$$a = \frac{F_Y}{{}^{W}\!/_{2g}}$$

Once acceleration is determined, the distance can be calculated as above. The distance that the mass moves between each data point can then be summed for the total *slide distance*. Dangerous sliding can occur at either of the braked wheels at two points during the trial, sitting down and then standing up. The most extreme of these four slide possibilities is then used in the design analysis.

Converging on a design parameter:

The above calculations can be used to find the relationship between any two variables if the other five are known. For example, if the affect of the *seat position* on the required *walker mass* must be determined, all other variables are held constant and an iterative procedure must be performed for each *walker mass* to isolate the *seat position* that will allow for the desired slip. *Any seat position* behind this value will be a safe design with respect to sliding, while positions further to the front will cause excessive sliding. The bisection method was used to converge on desired values. This simple method isolates a value by choosing an interval with the value within the high and low bounds. The method then systematically reduces the interval by splitting it in half at every iteration until it is smaller than some tolerance, in this case 5%. The computer program and accompanying documentation are listed in Appendix B.1.

3.3.2 Tipping

To examine the amount that the walker legs would rise above the ground, a similar analysis to that of sliding should be performed, but an angular displacement instead of a linear one would be required. This would involve relating the moment (M) to the moment of inertia (I) and the angular acceleration (α):

$$M = I \cdot \alpha$$

The moment of inertia is based on the sum of the products of the masses of each of the elementary particles. This requires detailed information about the design of each particular walker being considered. To avoid this problem, the displacement of the wheels from the ground can be approximated as linear since they only rise 2 cm over a 45 cm *wheel base*. The problem is reduced to the calculation of the acceleration of the center of mass. This assumption is validated in the following example.

In this example, the mass distribution of the walker is approximated by five lumped masses totaling 10 kg (22 lbm.) (Figure 3.10). If a moment of 4.5 $N \cdot m$ is applied about the contact point between one set of wheels and the ground, the linear and angular displacement of the other wheels can be compared.

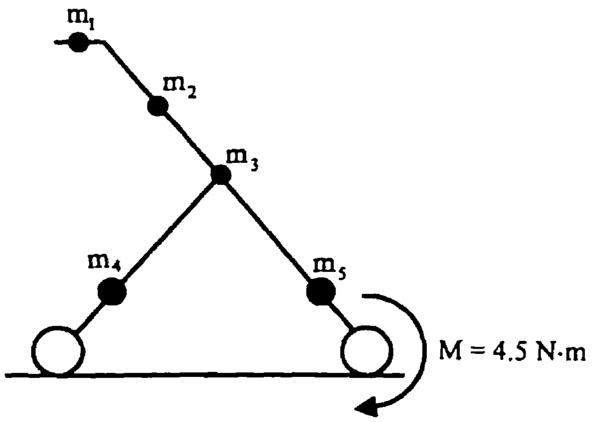


Figure 3.10 Model for calculating moment of inertia I

Angular displacement:

The first step is to calculate the moment of inertia. Multiplying the square of the distance to the point mass by the mass of each element and summing these values yields an I value of 3.6 kg m^2. The angular acceleration can now be calculated:

$$\begin{aligned} \alpha &= \frac{M}{I} \\ &= \frac{4.5\,\mathrm{N}\cdot\mathrm{m}}{3.6\,\mathrm{kg}\cdot\mathrm{m}^2} \\ &= 1.25\,{}^{\mathrm{rad}}\!/_{\mathrm{s}^2} \end{aligned}$$

The angular displacement of the *centre of gravity* is dependent on the angular acceleration and time:

$$\theta = \tfrac{1}{2}\alpha t^2$$

Over a small time increment (t = 0.25s):

$$\theta = 0.04\ \mathrm{rad}$$

This angle that the *centre of gravity* moves through is the same angle that the wheels will move from the ground which can be determined through trigonometry (Figure 3.11). This angular displacement causes the wheels opposite to the moment to rise of 1.76 cm.

Linear displacement:

To consider a linear displacement of the same wheels, the force at the *centre of gravity* due to the moment (F_c) must be found. A moment analysis is performed to locate the *centre of gravity* which is 53 cm from the point of rotation. A force of 8.5 N applied at a right angle to the rotation-to-centre point will cause an equivalent moment. The force is accelerating the entire mass of the walker ($^{W}\!/_{g}$):

$$a = \frac{F_c}{^{W}\!/_{g}} = 0.85\,^{m}\!/_{s^2}$$

The linear displacement (h_c) of the *centre of gravity* can now be calculated for t = 0.25:

$$h_c = \tfrac{1}{2}at^2 = 2.65\,cm$$

The height of the wheels (h) can then be calculated using similar triangles (Figure 3.11):

$$h = \frac{h_c \cdot b}{c} = 2.25\,cm$$

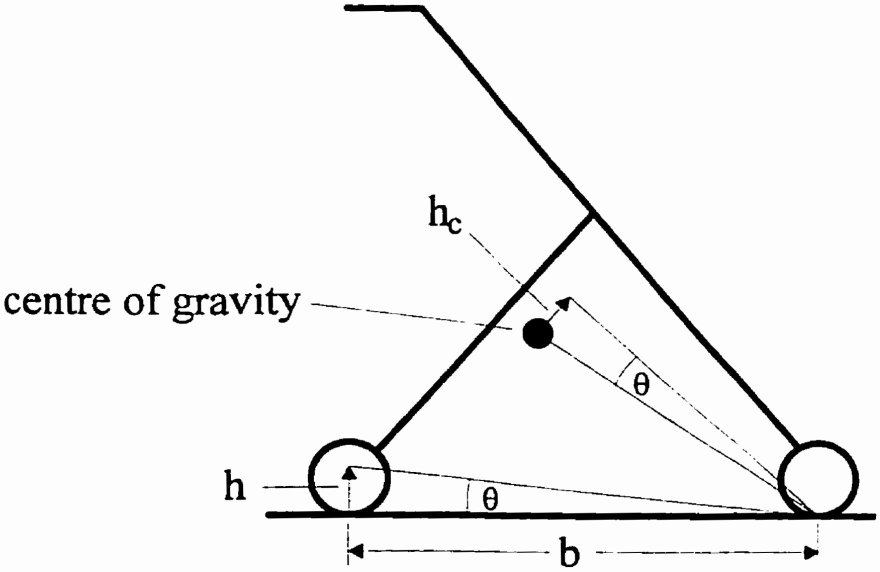


Figure 3.11 Relating movement of the centre of gravity to the wheel

The linear calculation results in a 2.25 cm rise verses a 1.76 cm rise in the angular case. This is a 22% difference on the more conservative side. By using the linear approximation, the moment of inertia will not have to be estimated for each different walker.

Tipping of the walker is only considered in the *yz*-plane with forces along the *x*-axis being minimal. It occurs about the braked wheels' contact point with the ground or the free wheels' axes (see Figure 1.4). At each instant, the location of the force vector relative to the braked wheel (*j*) can be found by using the same method as in the sliding analysis. The moment that the forces cause about the wheels can then be calculated.

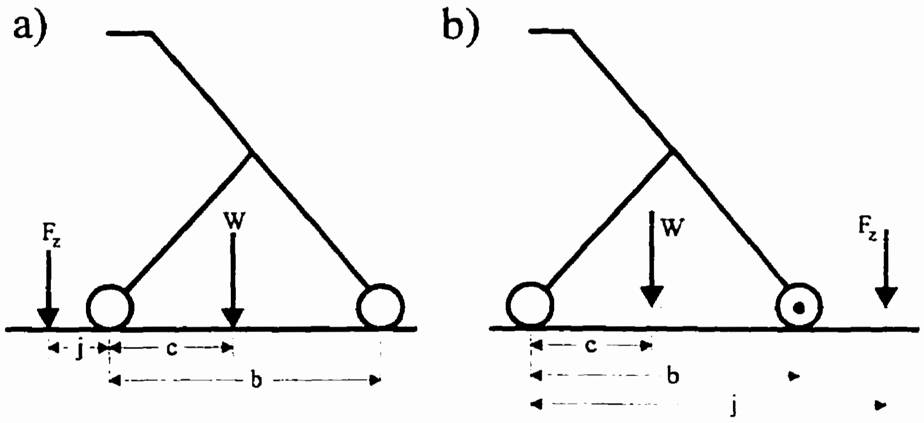


Figure 3.12 Calculating the moment about a) the braked wheels and b) the free wheels

To find the moment about the contact of the braked wheels and the ground (M_B), the applied force and the *walker weight* must be considered (Figure 3.12a). The applied force (F_Z) acts at a distance (*j*) from the braked wheels, causing a moment ($j \cdot F_Z$). The walker applies a force (W) that acts at the location of the *centre of gravity* (*c*) measured from the braked wheels.

$$M_B = j \cdot F_Z + W \cdot c$$

To find the moment about the free wheels' axles (M_F), the *walker weight* and applied force must be considered. The walker weight (W) causes a counter-clockwise, or negative moment about the free wheels. This force acts at a distance of $(b-c)$ from these wheels. Since this moment calculation is not about a point lying at the ground, an adjustment (k) of the location of F_Z must be made. Figure 3.12b shows the applied force and free wheel with the axle of the wheel a height of (r) above the ground.

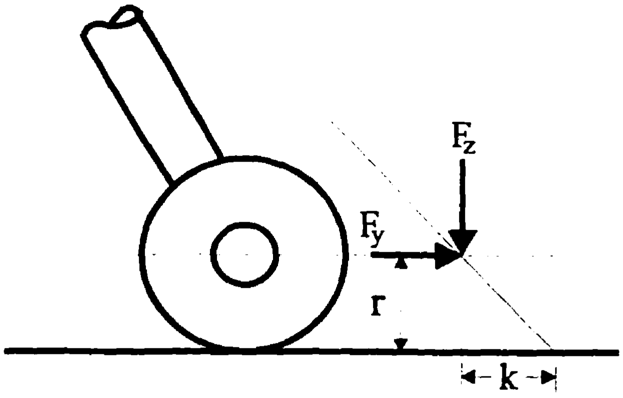


Figure 3.13 Adjusting for the moment about the axle

F_Z is then acting closer to the braked wheel calculated by similar triangles (Figure 3.13):

$$k = \frac{r \cdot F_Y}{F_Z}$$

The applied force (F_Z) is then acting at a distance $(j-b-k)$ from the free wheels. These forces result in a total moment of:

$$M_F = F_Z \cdot (j-b-k) - W \cdot (b-c)$$

With the moment about the free and braked wheels known, the linear model can be used to determine the amount that the wheels rise from the ground. First, the resulting force lifting the wheels that causes tipping can be found. The force acting at the braked wheels is dependent on the moment about the free wheels (Figure 3.14a).

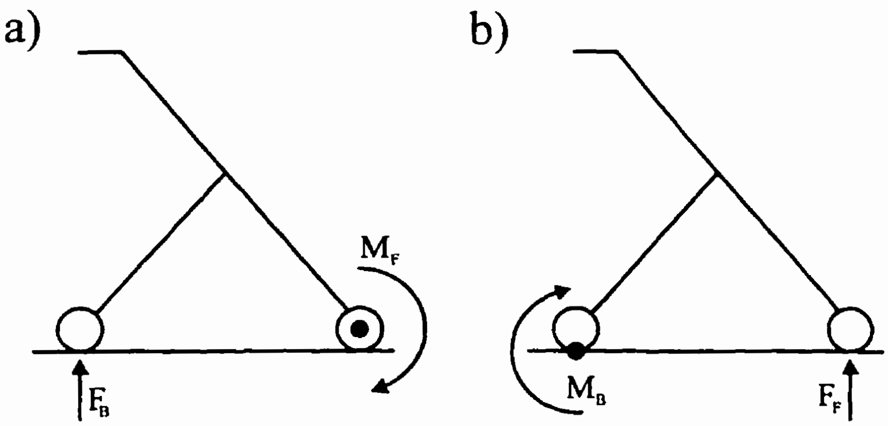


Figure 3.14 a) Calculating F_B based on M_F b) calculating F_F based on M_B

This moment (M_F) divided by the *wheel base* (b) will yield the lifting force at the braked wheels (F_B):

$$F_B = \frac{M_F}{b}$$

Similarly, the force acting at the free wheels, F_F is dependent on the moment about the braked wheels (Figure 3.14b). It is found by dividing this moment (M_B) by the *wheel base* (b). A negative moment will cause an upward, or positive force at the braked wheels:

$$F_F = \frac{-M_B}{b}$$

With the force on the wheels known, the distance that the wheels will rise above the ground can be determined. For the example of the braked wheels, the force (F_B) is pushing up the weight acting through the braked wheels [$W/g \cdot (1-c)$]. As in sliding, it is not known how much of the users weight is being tipped with the walker. The most conservative case would be to consider only the *walker weight* making tipping easier. This causes an acceleration of:

$$a = \frac{F_B}{W/g \cdot (1-c)}$$

Similarly, for the free wheels:

$$a = \frac{F_F}{W/g \cdot c}$$

As in the sliding analysis, the incremental distance (d_t) that the wheels rise above the ground over a small time interval (t) is:

$$d_t = \tfrac{1}{2} a t^2$$

Converging on a design parameter:

As with sliding, the above calculations can be used to find the relationship between any two variables if the other five are known. The bisection method was used to determine the design variables that would allow for tipping resulting of a rise of the free or braked wheels of 2 cm. The computer program and accompanying documentation are found in (Appendix B.2).

3.3.3 Brake failure

The allowable rolling distance is set at 5 cm, the same distance allowed for sliding. An estimate of the shear that the brake can withstand is made. The rolling distance that the shear forces greater than this value causes relative to 5 cm will guide the next estimate. This process is repeated until a distance of 5 cm is reached to within 5%.

The rolling distance once the shear force causes brake failure can be found as follows:

$$F_Y = W/2g \cdot a$$

where $^{W}\!/_{2}$ is half the weight of the walker, and a is the acceleration. All variables are known except for acceleration of the mass. Isolating for the acceleration:

$$a = \frac{F_Y}{^{W}\!/_{2g}}$$

Once a is determined, distance can be calculated. For a uniform acceleration:

$$d_s = V_o \cdot t + \tfrac{1}{2}at^2$$

where d is an incremental distance slid over a small interval of time (t). Assuming $V_o = 0$ over this short time span with constant acceleration:

$$d_s = \tfrac{1}{2}at^2$$

The distance that the mass moves between each data point can then be summed for the total distance rolled. The distance that a walker leg moves is not totaled over an entire trial. For each wheel, the distance during sitting is summed as well as the distance during rising, ending up with four slip distances. The most extreme is then compared to the allowable 5 cm roll. If the distance rolled is greater than 5 cm, a higher restrictive shear is required. An iterative process eventually converges on the answer. The computer program and accompanying documentation are provided in Appendix B.3.

3.4 Results

The design requirements will be based on the worst trial for all subjects. This will produce the most conservative designs of a walker that would perform safely for all subjects.

3.4.1 Sliding

For each *configuration*, there were two trials for the seven subjects. There are therefore 14 curves that can be generated when relating any two of the variables. In order to design a walker that would be safe for all seven of these subjects, it is necessary to select the worst case. This corresponds to the one curve of the 14 that requires the most extreme design.

An example of this can be seen when relating the *walker mass* to the *seat position*. For a given trial, the *walker mass* as a function of the *seat position* for all 14 trials is shown in Figure 3.15a. As the seat is moved closer to the free wheels, less of the user applied force is acting through the braked wheels. As the mass of the walker is increased, there is additional normal force at the braked wheels. This allows the seat to be positioned further away from the braked wheels.

Of the 14 curves, the data requiring the *seat position* closest to the braked wheels is the most conservative, and this becomes the design requirement since the design is to consider all trials of all subjects. Figure 3.15b shows the required design curve only with the other curves not shown. This result is the analysis of one *configuration* only. If the same process is applied to the other *configurations*, six curves can be displayed and each *configuration* can be compared Figure 3.15c.

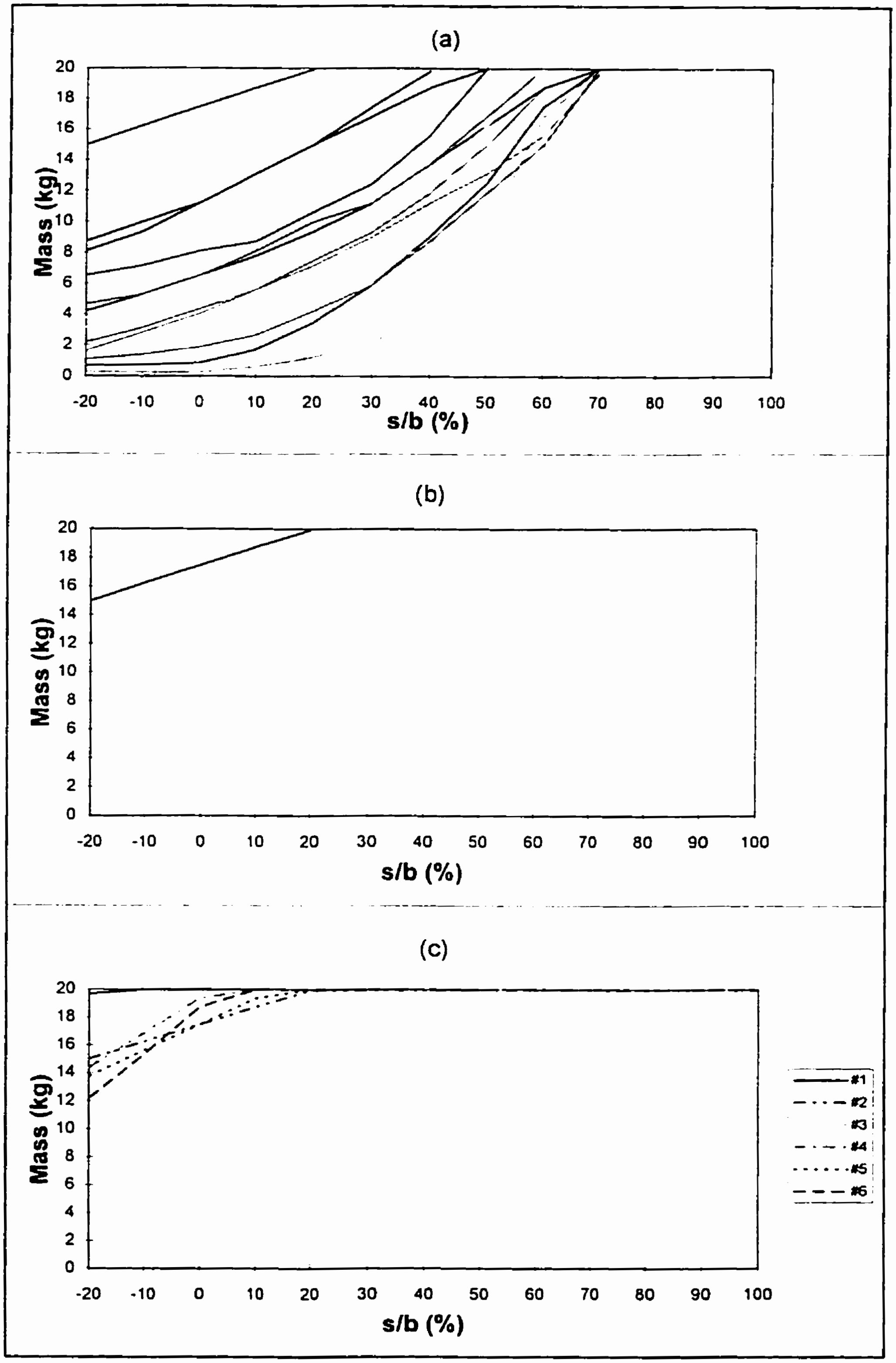


Figure 3.15 a) Seat position Vs walker mass for all 14 trials of one configuration b) Most conservative curve of the 14 trials c) Most conservative curves for all configurations

Design variables can be related to each other for a better understanding of walker design:

Seat position Vs Wheel base

As the *wheel base* grows, more of the user applied force is contained within the *wheel base*, and therefore distributed among the braked wheels. This allows the seat to be positioned closer to the free wheels while maintaining the same stability (Figure 3.16).

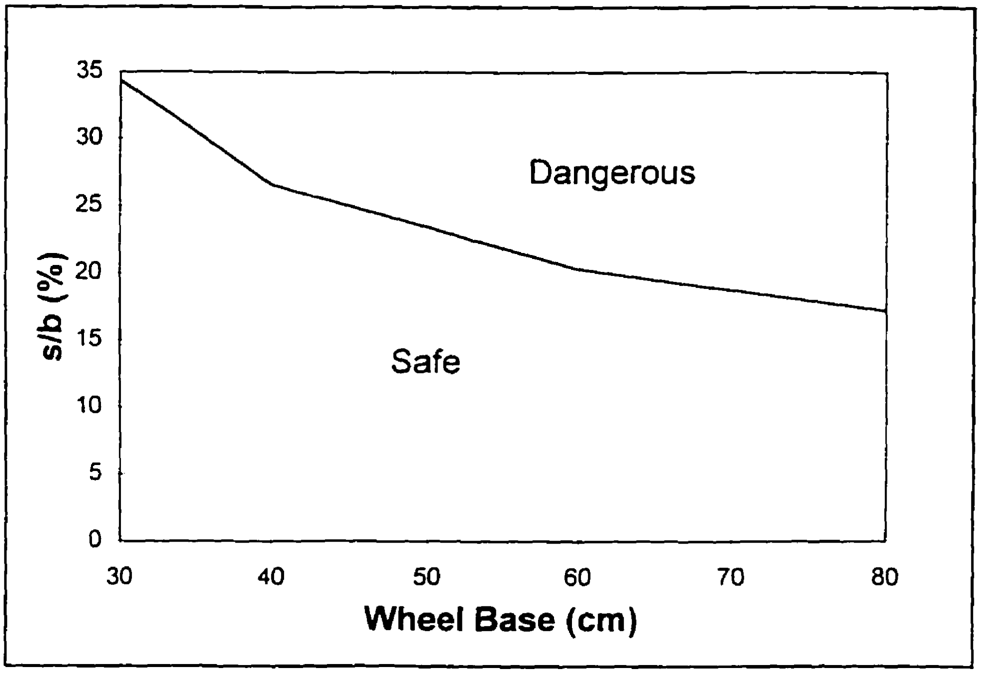


Figure 3.16 Seat position Vs wheel base

Seat position Vs Walker mass

With a movement of the *seat position* towards the front of the walker, less of the applied user force will act through the braked wheels. An increase in the *walker weight* will compensate for this (Figure 3.17).

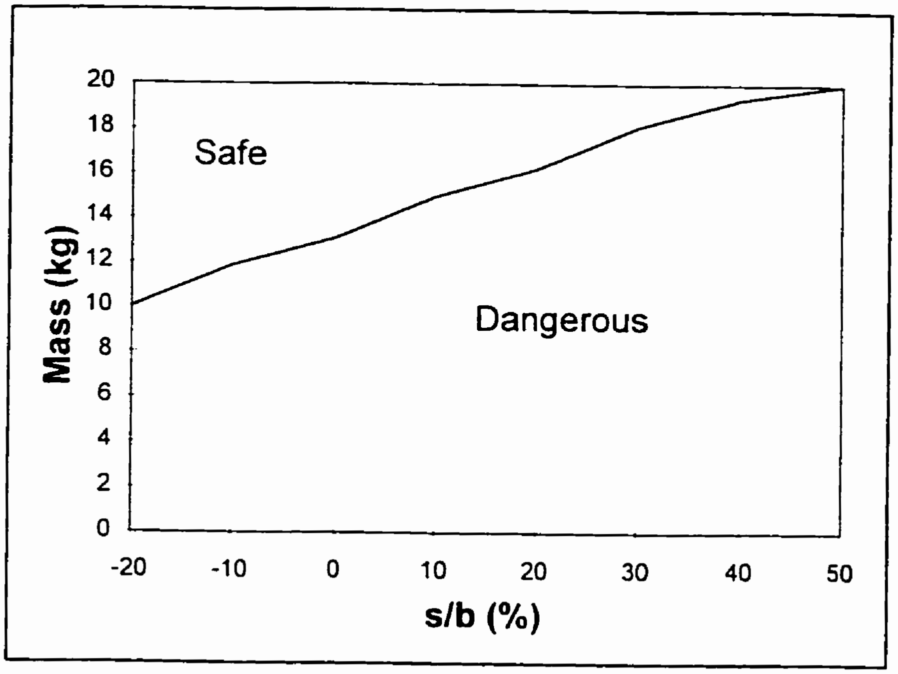


Figure 3.17 Seat position Vs wheel base

Centre of gravity Vs Walker mass

As the *centre of gravity* is moved closer to the front of the walker, less of the *walker weight* is acting through the braked wheels. The *walker mass* must therefore be increased (Figure 3.18).

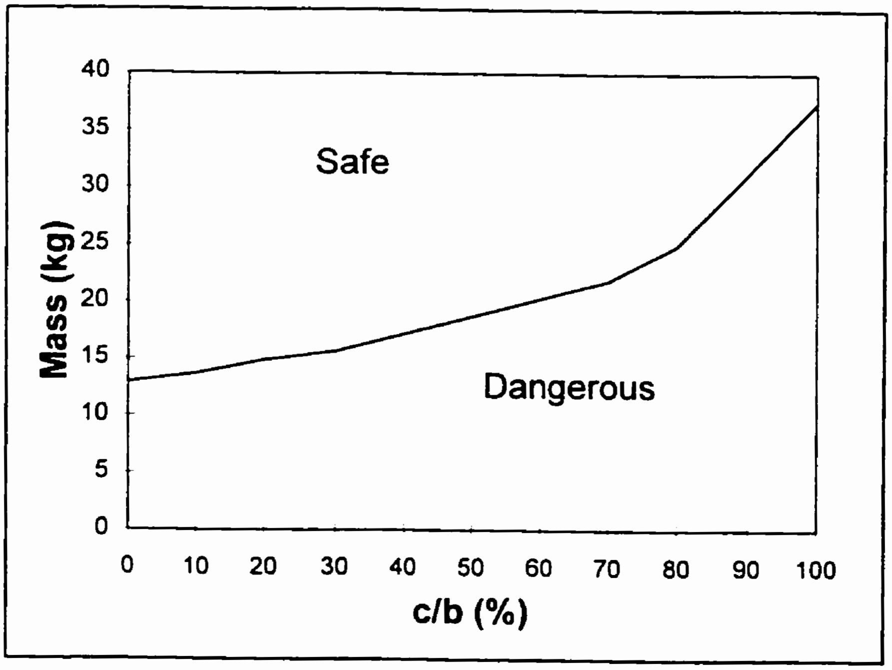


Figure 3.18 Centre of gravity Vs walker mass

3.4.2 Tipping

As in the sliding analysis, 14 curves can be generated for each *configuration* when relating any two of the variables. The curve requiring the most extreme design conditions will determine the design parameters with the other curves being ignored. Six curves can be displayed for each design variable relationship each representing the most conservative design for a *configuration*. The safety of each *configuration* can then be compared. Important variable relationships are seen below:

Seat position Vs Wheel base

As the *seat position* is moved towards the free wheels, the walker becomes prone to tipping forward. A longer *wheel base* will lessen the forward tipping moment by not allowing the forces to act as far outside of the *wheel base* (Figure 3.19).

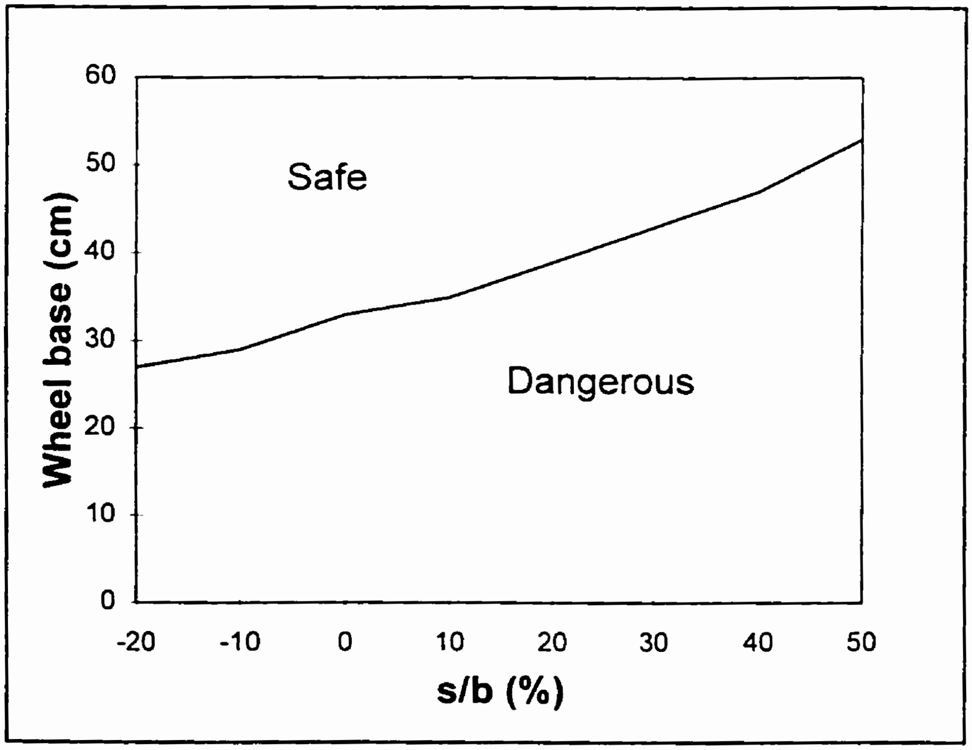


Figure 3.19 Seat position Vs wheel base

Seat position Vs Walker mass

Since the walker can tip in two directions, the *seat position* cannot be placed too far to the front or the back of the walker. When the seat is moved towards either extreme position, the applied forces tend to lie further beyond the *wheel base* and a higher *walker weight* is required. This weight applies a force within the *wheel base* which causes a stabilizing moment (Figure 3.20).

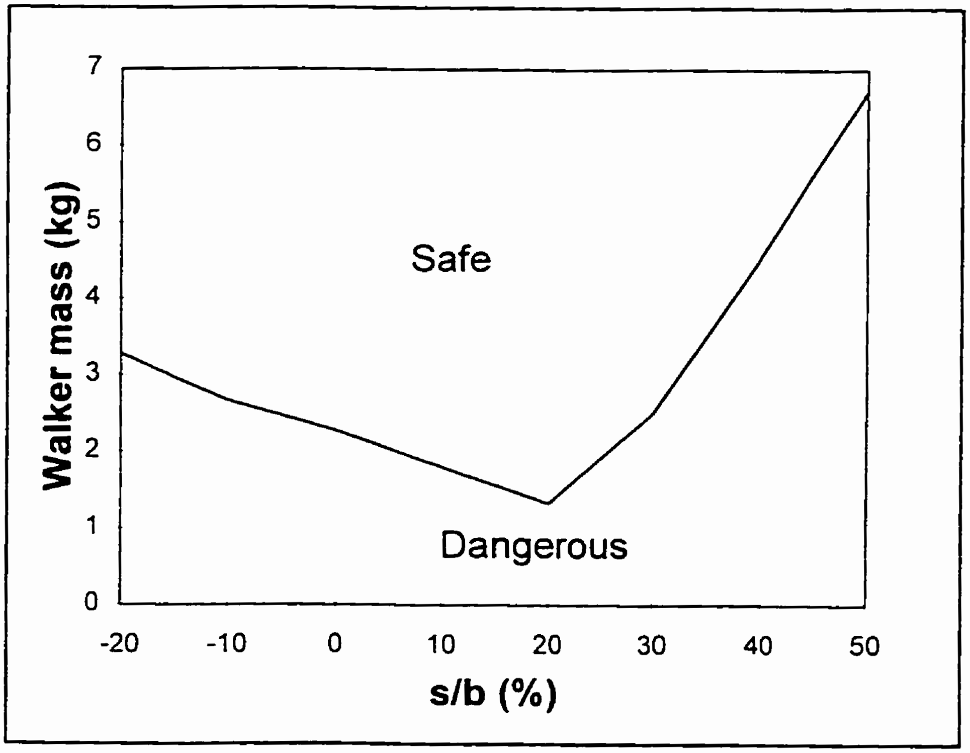


Figure 3.20 Seat position Vs walker mass

3.4.3 Brake failure

The two design variables that must be considered to avoid brake failure are the *walker mass* and the *brake shear*. The relationship of the *walker mass* as a function of the *brake shear* can be calculated for each trial. Similar to the analyses of the other modes of failure, 14 curves can be generated for each *configuration*. Of these curves, the highest one requires the greatest *brake shear* to avoid excessive rolling. The most extreme trial of all six configurations are shown in Figure 3.21.

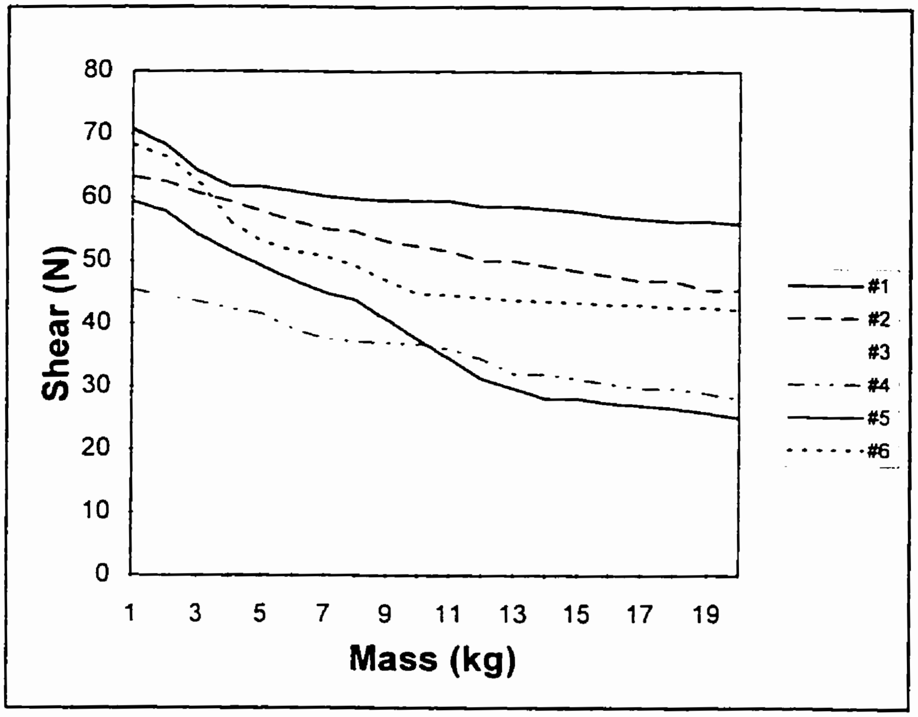


Figure 3.21 Required shear and mass for all configurations

3.4.4 Table of design requirements

Generating the table values:

The tables report the minimum required *walker mass* that will avoid both sliding and tipping for any combination of design variables. Values were obtained by taking the worst sitting trial and the worst tipping trial for each combination of variables. Data were then combined into one curve that represented the worst case considering both modes of failure. These tables are produced in Appendix C.

Interpreting the tables:

With six adjustable variables, and two being held constant (*slide distance* and *tipping height*), tables can be created that will allow designers to determine safe parameters for sitting and rising from a walker. For each *configuration*, walker design will be based on the following variables: *wheel base, walker mass, centre of gravity, coefficient of friction,* and *seat position.* The *seat position* can be related to the *walker weight* for different *centre of gravity* values. This table can be repeated for all combinations of *wheel base* and *coefficient of friction* ranges. An example of these tables can be seen in Table 3.1.

s/b

		-20	-10	0	10	20	30	40	50
	10	16	9	8	8	10	12	14	17
	20	9	8	8	9	10	13	16	18
c/b	**30**	7	8	8	9	11	14	17	19
	40	8	8	9	10	12	15	18	+
	50	8	9	10	11	13	16	19	+
	60	9	10	11	11	14	18	+	+
	70	9	11	11	13	16	+	+	+

Table 3.1 Example of design table found in Appendix C

A table exists for each combination of *configuration* (× 6), *coefficient of friction* (× 2), and *wheel base* (× 5), for a total of 60 tables. Determining the *configuration* is the first step in isolating the most useful table. Tables of *wheel base* and *coefficient of friction* combinations are then found within each *configuration* heading.

Each table reports the minimum required *walker weight* that will allow for safe sitting on a walker. Down the left side of the table is the horizontal *centre of gravity* location (c) divided by the *wheel base* (b) × 100. These values range from 10% to 70% as mentioned above. Along the top of the table is the *seat position* measured from the braked wheels divided by the *wheel base* × 100. These values range from -20% (behind the wheels) to 50% of the *wheel base.*

Each cell of the table represents the minimum required *walker mass* measured in kilograms for all combinations of the *seat position* and *centre of gravity* ranges. If the required *walker mass* is 20 kg or greater, the value of the cell is represented with a "+" symbol. The purpose of this symbol is to be able to focus on the useful ranges of the table as well as observe the trends easily. The average mass of the existing walkers that were measured was about 10 kg. Gray shading fills the cells with mass values of 10 kg or less. This helps to highlight the more realistic mass values.

Design parameters may fall between values represented within the tables. In this case, interpolation is required. For example, if the *configuration* lies between #4 and #5, the appropriate minimum required *walker mass* should be found for each *configuration* and interpolation should then be performed.

Determination of variable ranges:

The range reported in the tables for each variable was set up to 200% of the maximum measured values found in four typical walkers.

Centre of gravity

Results have shown that the *centre of gravity* should be as close to the braked wheels as possible to avoid sliding. Existing walkers have the *centre of gravity* at about 60% of the *wheel base*. The *centre of gravity* range reported in the tables is from 10% to 70% of the *wheel base* in increments of 10%.

Seat position

Results indicate that the *seat position* should be as close to the braked wheels as possible to avoid sliding. Existing walkers have the *seat position* up to 48% of the *wheel base.* The range for the *seat position* was varied from -20% (behind the braked wheels) to 50% of the *wheel base* in increments of 10%.

Walker mass

The *walker mass* is the one variable that was calculated by the programs. With existing walkers with masses of about 10 kg, the highest *walker mass* considered in the tables is 20 kg.

Coefficient of friction

Only two values of μ, 0.4 and 0.8, were used when generating the data. This range corresponds to the value of the worst performing tire as determined in Chapter 2 and the highest value found on present day walkers.

Wheel base

Measurements from existing walkers show that, of four top selling walkers, the *wheel bases* range from 44 cm to 49 cm. This narrow band indicates that this variable does not have a great deal of flexibility. Consequently, values ranging from 35 cm to 55 cm in 5 cm increments were used in the tables.

Configuration

The combinations of the above five variables were calculated for each of the six *configurations*.

4. Discussion

4.1 Evaluation of design parameters

Configuration

The *configuration* that has the most cells in the table with values of 10 kg or under can be considered the safest (Table 4.1). From the ranking, #3 is the safest with #2, #5 and #6 being the second safest (see Figure 2.1 for *configuration* dimensions). From the questionnaire, *configuration* #6 was chosen as the most comfortable with #3, #4, and #5 being the next most comfortable. Since #3 is the safest and the second most comfortable, and #6 is the most comfortable and second safest, these two *configurations* are the best of the six tested.

Configuration	$\mu = 0.4$	Rank	$\mu = 0.8$	Rank
1	0	4	2	4
2	0	4	118	3
3	111	1	210	1
4	2	3	29	4
5	10	2	111	3
6	1	3	156	2

Table 4.1 Evaluation of the safest configuration

Centre of gravity and *Seat position*

These two variables are closely related and the best position for one cannot be considered without the position of the other. From the tables, the lowest mass requirements, and therefore the best designs, often form along a certain *seat position-centre of gravity* relationship. For high *centre of gravity* values, the required *seat position* is close to the braked wheels. This is because the *centre of gravity* closer to the free wheels will not transmit as much normal force through the braked wheels. By moving the seat closer to the braked wheels, more of the user applied force will act through the braked wheels. As the *centre of gravity* moves closer to the braked wheels, more of the *walker mass* will be supported by the braked wheels and the allowable *seat position* will be closer to the free wheels. A *seat position* close to the braked wheels can avoid sliding, but the further towards the back of the walker the seat is placed, the more prone to tipping the walker becomes.

Coefficient of friction

Clearly the higher the *coefficient of friction* between the tire and the ground, the less likely the walker is to slide. Cost and durability may be deterrents to the selection of better tires.

Wheel base

Although longer *wheel bases* are safer, as the walker becomes longer, it becomes harder to manoeuver. The device is also not as compact and can become awkward.

Walker mass

A heavier walker is clearly safer when dealing with tipping and sliding, yet some consumer opinion and most marketing departments consider a lighter walker more appealing for a number of reasons. A lighter walker feels easier to push and steer allowing for more control with less effort. Walkers are often lifted into the trunks of cars. A heavier walker becomes a burden on someone assisting a walker user. The mass and position of the mass of a walker must be considered carefully to create safe *and* practical sitting situations.

Slide distance

The difference between allowing for no sliding and for minimal sliding that will not be felt by the user can alter the design drastically as illustrated in the following example. Figure 4.1a shows the shear/normal graph of a sample trial that allows for a sliding distance of 0 cm at μ = 0.4. To make this possible, the normal force acting through this braked wheel would have to be 67 N. This could translate into a *walker weight* of 34 kg. To allow for a 5 cm slip, the normal force through the braked wheels would have to be only 37 N with the result shown in Figure 4.1b. The area above μ=0.4 indicates a 5 cm slip. This example clarifies the need to design the walker to permit limited sliding.

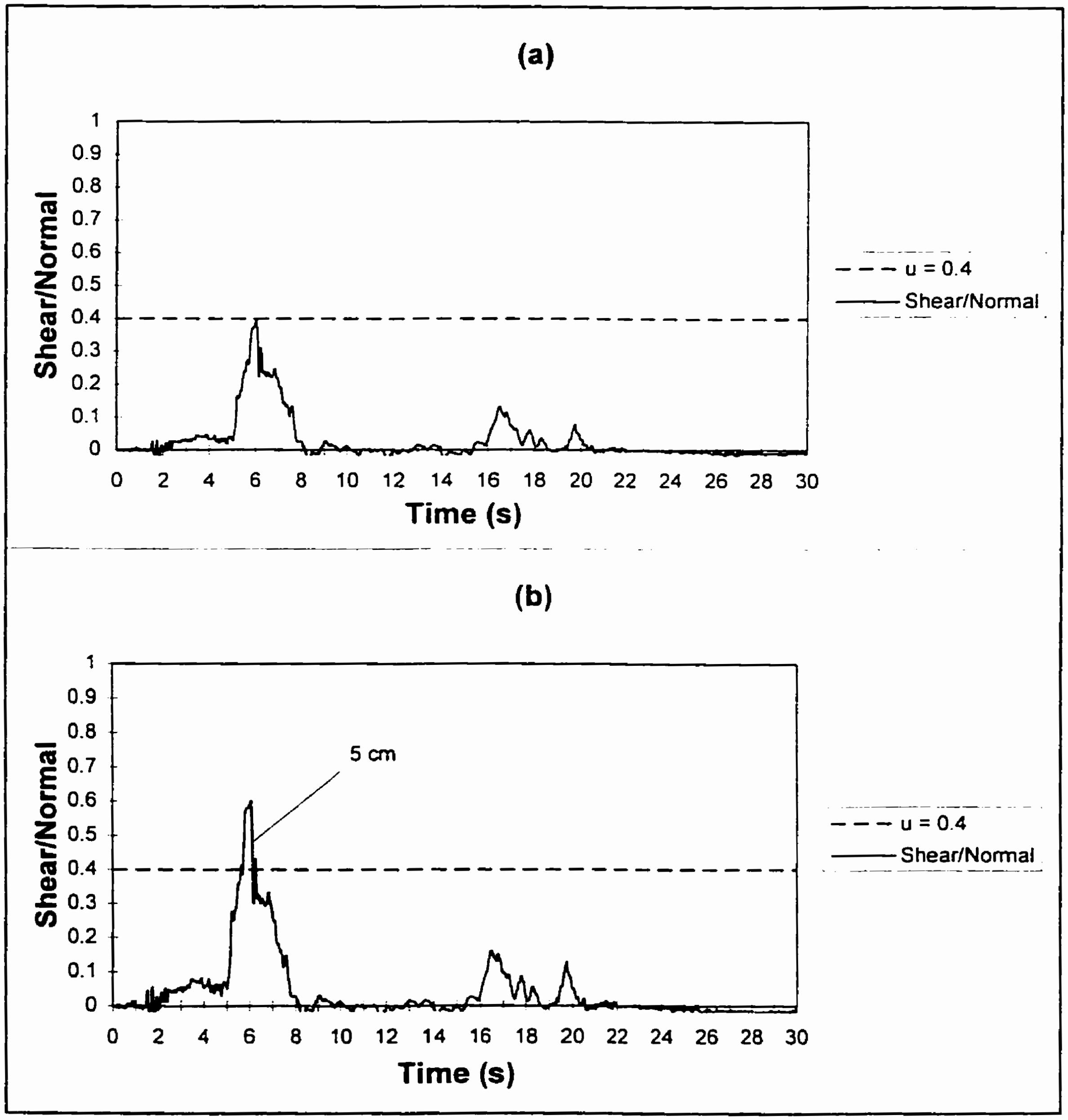


Figure 4.1 Designing for a) 0 cm slide b) 5 cm slide

There is no need to add an additional 30 N to each leg to prevent all sliding. The *slide distance* design parameter will be held at 5 cm to reduce the number of variables in the analysis.

Tipping height

As in sliding, the difference between allowing for no tipping and for limited tipping can require very different designs. Figure 4.2a shows the moment about the free wheels. This moment includes the applied force of the user and the *walker weight*. To avoid any tipping, the moment must be negative at all times. This requires a *walker mass* of 17.5 kg. Allowing for a 2 cm (Figure 4.2b) rise of the wheels would lower the required *walker mass* to 9.7 kg. The additional 7.8 kg is unnecessary to avoid only 2 cm of lift and allows the designer much more freedom when selecting appropriate design parameters.

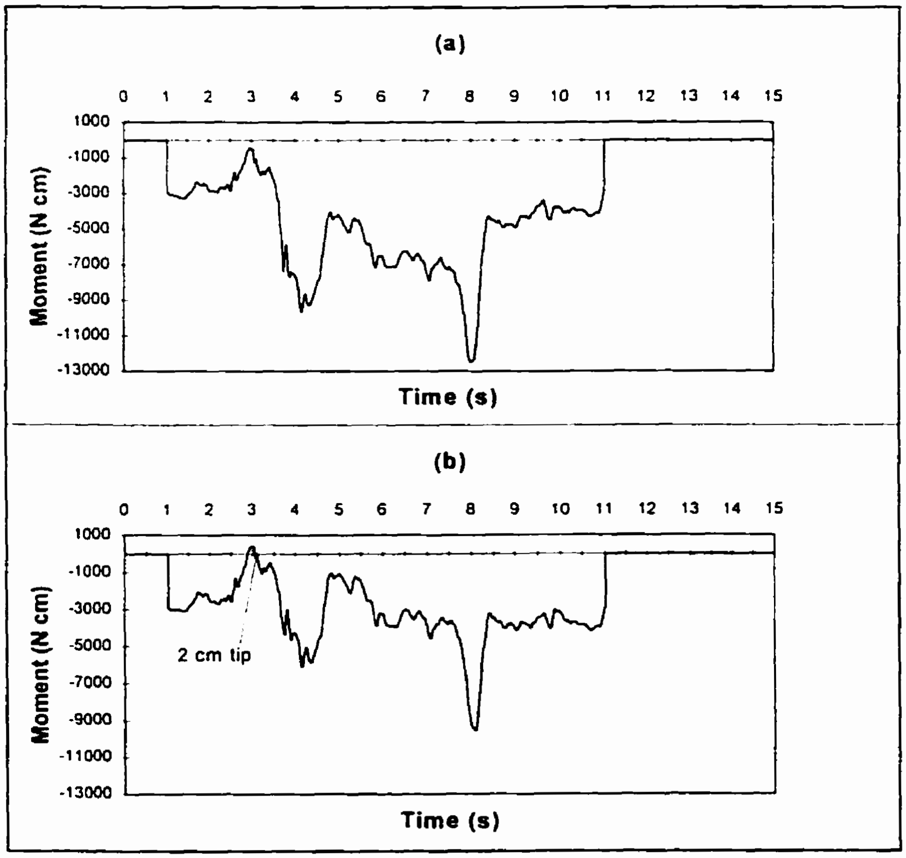


Figure 4.2 Designing for a) 0 cm tip b) 2 cm tip

4.2 Present day Vs future walker designs

4.2.1 Measurement of present day walker design parameters

Characteristics of four top-selling walkers were measured. These measurements were translated into the design variables which could then be compared to the required design minimums generated in Chapter 3.

All measurements except for the *coefficient of friction* were direct using a plumb-bob, tape measure, and a pelouze® electronic scale (± 5 g). To help calculate the *coefficient of friction* for different walkers found in showrooms and stores, a portable *coefficient of friction* measuring device was constructed (Figure 4.3). This device was designed to hold the wheel at the axle to prevent any horizontal movement. The wheel rested on a ceramic tile. This material was used because it was the common flooring material that resulted in the least amount of friction in the experiment that obtained the coefficients of friction for different wheels (see Chapter 2).

Figure 4.3 Portable coefficient of friction measuring device

A measured horizontal shear force was applied by pulling on a strap that was wrapped part way around the circumference and passed over the top of the wheel. This force, applied through a fish scale, was slowly increased until wheel rotation was observed. At this point, the applied shear was recorded with an accuracy of ± 0.125 kg.

This test was repeated three times. To determine the weight distributed through each of the wheels, the scale was placed under each wheel while raising the other wheels to keep the walker level. The weight distribution of each wheel could then be determined. The raw measurements were then converted into the design parameters:

Wheel base

The *wheel base* was measured directly.

Seat position

The *seat position* as a percentage of the *wheel base* was calculated by dividing the measurement (s) by (b).

Walker mass

The walker mass was calculated by summing the weight measurements under each wheel.

Centre of gravity

The *centre of gravity* was calculated by performing a moment analysis about the braked wheels using the *walker weight* at each wheel. The weight at the free wheels and the total *walker weight* were used.

Coefficient of friction

The averaged shear value required to move the wheel was divided by the measured *walker weight* being supported by that wheel.

Configuration

Walker designs will not necessarily match a *configuration* type exactly and some interpolation may be required. The *configuration* closest to that of the walker in question must be determined. First the seat height is considered. *Configurations* #1, 2, and 3 have a seat height of 63 cm (25 in.) and #4, 5, and 6 are 53 cm (21 in.) high. The relative handle position must then determined. This is measured horizontally from the back of the seat edge to the centre of the handle. This dimension should then be matched to the closest *configuration* in Figure 2.1. The design parameters of the four walkers are summarized in Table 4.2.

Parameter	SkyWalker	Opal	Riva	Elan
μ	0.4	0.8	0.6	0.5
s/b	27%	36%	48%	41%
c/b	60%	57%	62%	61%
mass	11 kg	9 kg	10 kg	8.5 kg
config.	5 to 6	5 to 6	6+	3 to 6
b	44 cm	45 cm	46 cm	49 cm

Table 4.2 Design parameters of four sample walkers

4.2.2 Performance of present day walkers

The SkyWalker

The SkyWalker is available in four heights ranging from 48 cm (19 in.) to 63 cm (25 in.). The model that was tested (Figure 4.4) has a seat height of 53 cm (21 in.), which makes it one of *configurations* #4, 5, or 6. The horizontal distance from the seat edge to the centre of the handle is about 8 cm. The closest *configuration* is #6, which actually has the handle 12.7 cm away.

Figure 4.4 The SkyWalker

With the *coefficient of friction* of 0.4 and a *wheel base* of 44 cm, the relevant table is found in (Appendix C) and is duplicated in Table 4.3. Reading the table for a *centre of gravity* of 60% of the *wheel base* and a *seat position* to *wheel base* ratio of 27%, the required *walker mass* must be above 20 kg to avoid sliding of 5 cm and tipping of 2 cm off the ground. The SkyWalker has a mass of only 11 kg making the present design unacceptable.

Wheel base = 45 cm

$\mu = 0.4$

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	13	15	18	+	+	+
20	19	13	14	17	19	+	+	+
30	14	13	15	18	+	+	+	+
40	12	14	17	+	+	+	+	+
50	12	16	19	+	+	+	+	+
60	14	18	+	+	+	+	+	+
70	16	+	+	+	+	+	+	+

Table 4.3 Relevant table from Appendix C to evaluate the SkyWalker

Recommended improvements:

If a *coefficient of friction* of 0.4 is kept, drastic measures will have to be taken to avoid the need to add to its weight. If the *configuration* is not altered, one possible adjustment would be to lengthen the *wheel base* to 55 cm and move the *seat position* to -20% of the *wheel base*, or 8.8 cm behind the braked wheels. If the *configuration* is changed to #3 by raising the seat, with no *wheel base* adjustment the *seat position* will have to move to 0% of the *wheel base* (directly over the braked wheels), less than a 30% change.

If the *coefficient of friction* is increased to 0.8, the required mass would be about 12-13 kg. The walker would barely be heavy enough. With this higher coefficient, if the *seat position* was brought towards the back of the walker by 10% of the *wheel base*, or the *centre of gravity* was shifted 20% of the *wheel base* closer to the braked wheels, the walker would perform acceptably. If the *wheel base* is expanded to 55 cm, the *walker mass* will then be acceptable.

The Opal 2000

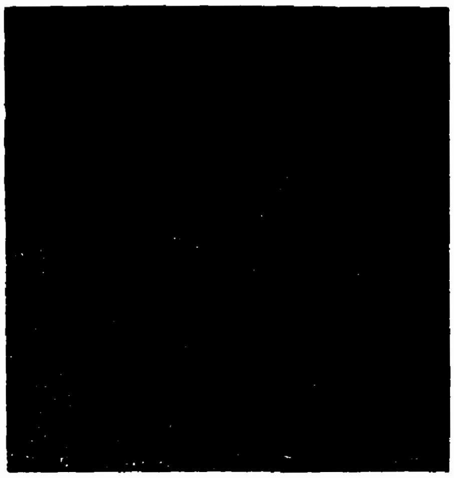


Figure 4.5 The Opal 2000

The model of the Opal 2000 that was measured has a *configuration* closest to #6 (Figure 4.5). With a *coefficient of friction* of 0.8 and a *wheel base* of 45 cm, the table to evaluate the Opal's performance is duplicated in Table 4.4. With a *centre of gravity* of 57% and a *seat position* 36% of the *wheel base* from the braked wheels, the required *walker mass* is about 16 kg, yet the Opal 2000 only weighs 9 kg.

Wheel base = 45 cm

s/b

		-20	**-10**	**0**	**10**	**20**	**30**	**40**	**50**
	10	+	+	13	5	5	7	10	13
	20	19	13	7	5	5	8	11	15
c/b	**30**	14	10	6	5	6	9	13	16
	40	12	8	5	5	7	10	14	18
	50	10	7	6	6	8	12	16	+
	60	9	6	6	6	9	14	19	+
	70	8	6	6	7	10	17	+	+

Table 4.4 Relevant table from Appendix C to evaluate the Opal 2000

Recommended improvements:

The *walker mass* can be increased to 16 kg, but this becomes a very heavy device. Without increasing the mass, but moving the seat and handles about 15% (7 cm) towards the braked wheels, the required mass drops under 9 kg (the current mass) resulting in an acceptable design. If the seat ratio is to remain constant, the *centre of gravity* has to be moved back to 20% of the base from the braked wheels. Smaller adjustments of the *seat position* and *centre of gravity* combinations can also result in safe designs. Increasing the *wheel base* will help to create a safer design, but adjusting the base to 55 cm alone will not stabilize the walker enough.

By raising the seat to create a *configuration* #3 seat-handle relationship, the walker becomes very close to being safe. Minor adjustments of any one of the other variables would then create a safe design.

The Riva

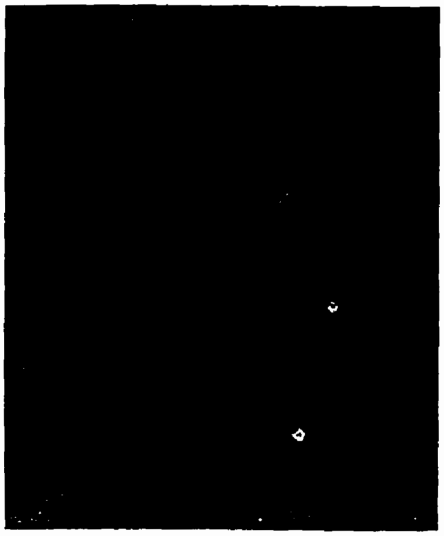


Figure 4.6 The Riva

The handles of the Riva model tested actually lie further in front of the seat than any other tested *configuration* with the closest *configuration* being #6 (Figure 4.6). With a coefficient of 0.6, interpolation will have to be performed across tables. With a *wheel base* of 46 cm, the two tables that will evaluate the Riva's performance are found in Tables 4.5a and 4.5b. With a *centre of gravity* of 62% and a *seat position* of 48%, the required mass is above 20 kg on both tables. These mass values are well beyond the 10 kg mass of the walker.

Wheel base = 45 cm
$\mu = 0.4$

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	+	+	13	15	18	+	+	+
20	19	13	14	17	19	+	+	+
30	14	13	15	18	+	+	+	+
40	12	14	17	+	+	+	+	+
50	12	16	19	+	+	+	+	+
60	14	18	+	+	+	+	+	+
70	16	+	+	+	+	+	+	+

Wheel base = 45 cm
$\mu = 0.8$

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	+	+	13	5	5	7	10	13
20	19	13	7	5	5	8	11	15
30	14	10	6	5	6	9	13	16
40	12	8	5	5	7	10	14	18
50	10	7	6	6	8	12	16	+
60	9	6	6	6	9	14	19	+
70	8	6	6	7	10	17	+	+

Table 4.5 Relevant tables from Appendix C to evaluate the Riva

Recommended improvements:

The extreme *seat position* of the Riva creates a very hazardous sitting situation. Only extreme design alterations can improve its performance. The most significant adjustment would be to raise the seat creating *configuration* #3. A 30% adjustment of the *seat position* towards the back of the walker would then create a safe design.

The Elan

The model of the Elan tested is the lightest of the walkers with a mass of only 8.5 kg with the longest *wheel base* of 49 cm (Figure 4.7). It's *configuration* lies between #3 and #6 therefore requiring interpolation. With a coefficient of 0.5 (rounded to 0.4), the two tables that will be of use are Tables 4.6a and 4.6b. With a *centre of gravity* of 61% and a *seat position* of 41%, the required mass is above 20 kg for both tables.

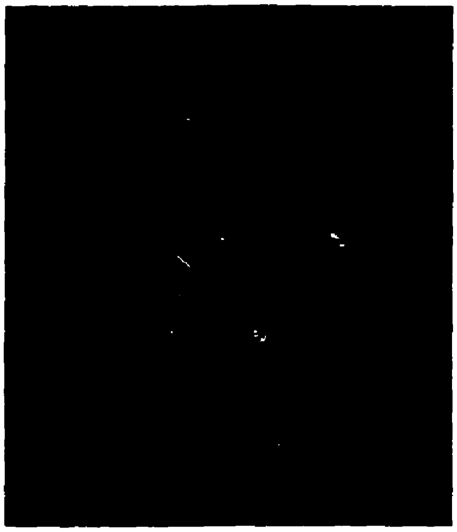


Figure 4.7 The Elan

Configuration #3
Wheel base = 50

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	+	9	7	8	9	11	14	16
20	13	7	8	8	9	12	14	18
30	9	8	7	8	10	13	16	19
40	8	8	8	9	11	14	17	+
50	8	7	8	10	12	15	19	+
60	8	9	10	11	13	16	+	+
70	9	10	11	13	14	19	+	+

Configuration #6
Wheel base = 50 cm

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	+	+	12	14	17	19	+	+
20	+	13	13	16	18	+	+	+
30	15	11	14	17	+	+	+	+
40	12	13	16	19	+	+	+	+
50	11	14	18	+	+	+	+	+
60	13	16	+	+	+	+	+	+
70	14	19	+	+	+	+	+	+

Table 4.6 Relevant tables from Appendix C to evaluate the Elan

Recommended improvements:

The most drastic yet simple improvement to the walker would be to add higher *coefficient of friction* wheels. With this improvement, the walker is almost within acceptable limits. A slight adjustment of the *seat position* or *centre of gravity* will make the existing mass acceptable. The mass can also be increased by 1-2 kg. If the *coefficient of friction* was not adjusted, a small increase to the seat height would make the walker be considered as *configuration* #3. Combinations of *seat position* and *centre of gravity* ranging from -20% and 50% respectively, to 10% and 20% respectively would then become acceptable.

4.3 Suggested future walker design

Design of walker for sitting:

An ideal walker design to ensure safe sitting and rising would have a high *coefficient of friction* ($\mu = 0.8$). The *configuration* would be #3 which is the safest, and second most comfortable. The ***wheel base*** would be 40 cm to allow for a compact and attractive design. For these variable values, Table 4.7 could then be referred to to determine the other values. The *seat position* would be directly over the braked wheels (0%) and the *centre of gravity* would be 30% (12 cm) from the braked wheels. This would allow for the safest design parameters for sitting and tipping while considering appearance and performance.

Wheel base = 40 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	13	8	4	5	5	7	13	+
20	8	5	6	5	5	8	15	+
30	6	5	5	5	6	8	17	+
40	5	5	5	5	5	10	19	+
50	5	5	6	6	7	11	+	+
60	6	6	6	7	8	14	+	+
70	6	6	7	8	9	18	+	+

Table 4.7 Relevant table from Appendix C for suggested design

Design for optimal weight distribution:

Walker users generally like a lighter walker. A common complaint when using heavier walkers is that the device becomes too cumbersome to lift in and out of the trunk of a car. Yet, the results of this study show that a heavier walker is more stable. One design possibility that will apply significant force through the braked wheels while allowing for easy lifting of the walker is to place removable weights on the legs of the braked wheels (Figure 4.8). The walker will be safe when used as a seat, and if the walker needs to be lifted, the weights can be removed individually and then the walker can be easily lifted as well. The placement of the weights over the braked wheels will create a centre of gravity closer to the back of the walker.

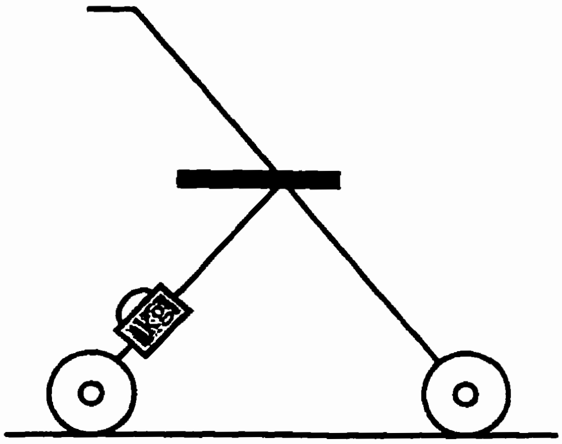


Figure 8 Detachable weight design

Design for sitting and walking:

With limited knowledge of dynamic walker use, only theoretical walker designs can be proposed that will consider both a parked walker and one used for walking. With a *seat position* this far back, the walker users will not have the freedom to swing their legs when walking. The seat may impede the natural walking pattern and the knees may collide with the seat edge. To avoid this potential problem, the seat could remain in a vertical position while the user is walking (Figure 4.8). When the user would want to sit, she would not consider sitting until the seat was horizontal. This would only happen by locking the brakes. The seat would then drop down over the braked wheels creating a safe sitting situation.

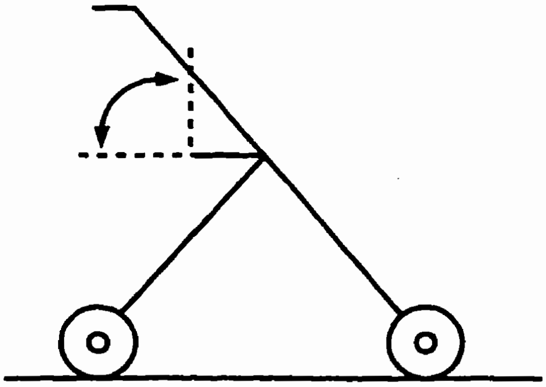


Figure 4.9 Design for walking and sitting

5. Conclusion

5.1 *Findings*

Models of walker use were used to generate tables that relate the variables involved in the tipping and sliding modes of failure. These tables can be applied to proposed or existing walker designs to evaluate performance or aid in design decision making. The requirements to avoid brake failure only involve the walker mass and the brake shear and were not included in the tables of sliding and rolling requirements. Only one graph (Figure 3.21) was needed to relate the required shear for each configuration that the brake must withstand to avoid 5 cm of rolling.

The data show that all present day walker designs are potentially dangerous when used as seats. Existing designs may slide along the ground or tip backward or forward causing at best, anxiety and at worst, serious injury. To create a safer mobility aid, the seat and centre of gravity should be placed closer to the braked wheels. This will transmit greater normal forces through the braked wheels and less sliding will result.

5.2 *Limitations of study*

The greatest limitation of this study is that it only focuses on the static use of walkers. Walker design cannot be based on this work alone. The results generated from this work may create a walker design that is dangerous during walking. The limited sample size of typical walker users only allows trends to be studied. The numbers in the design tables only apply to the seven subjects tested. The data do not represent the design requirements for the entire population.

While developing the mathematical models that simulate the walker reaction to a force applied by the user, three assumptions were made. The first involved the walker mass being evenly distributed about the sagittal plane. The tipping mode of failure was only considered in two dimensions. This assumed that the axis of tipping remains constant and there is no twisting of the walker. The sliding mode considered the movement of the wheels in two dimensions as well. The stroke victim, a common walker user, often has asymmetrical disabilities. Uneven distribution of the user applied forces through the walker could result from this condition. This issue was not explored.

The second assumption considered the *walker weight* as distributed perfectly based on the *center of gravity*. The left and right wheels of the braked or free wheels are assumed to share the load equally. Due to variations in manufacturing and uneven floor surfaces, there is no way to ensure that the wheels will all contact the ground evenly. This creates a more dangerous scenario than considered in this study with less walker normal force acting through the braked wheels.

The third assumption dealt with the sliding and rolling analysis where the shear force at each wheel was considered to be acting on half of the *walker weight* with movement resulting in a straight line. The walker will actually twist as movement begins. If both braked wheels are not moving at the same time, the walker will rotate about the fixed wheel.

The permissible slide and roll distance was limited to 5 cm and the tipping height was limited to 2 cm. The design tables do not consider more or less conservative values. The case of sliding being followed by rolling was not examined. The worst case for this combination would result in a 10-15 cm movement of the walker which is unacceptable.

All analyses were based on the walker resting on a flat surface. If the walker is parked on a hill, there is an increased danger of walker failure.

5.3 Future work

Continuing studies of walker design should focus on their dynamic use. A similar study could be performed that examines the possible modes of failure while walking. These may include tipping, instability with loss of balance, and difficult brake application. Following the example of this study, the user applied forces could be measured for an ideal case. These data could then be used to model how different walker designs will perform.

Appendix A - Subject consent form

CONSENT FORM

I have been asked to participate in a study which is seeking to improve walker parking brake performance. The study will be conducted at The Centre for Studies in Aging at Sunnybrook under the direction of Dr. Geoff Fernie. Joshua Finkel will be responsible for conducting the tests at Sunnybrook and can be reached at 416-480-5858 to answer any questions.

I will be interviewed by Joshua Finkel and first asked to answer some general questions about my age, abilities, and walker usage. My height and weight will be measured. I will not be required to wear special clothes for this test.

The walker apparatus will be placed on a special floor surface that measures forces. I will be asked to approach the walker, st down on it, and then get up. This will be done a total of 12 times using varying seat positions. After every 2 sittings I will be given a rest period of 3 minutes. The entire test will take approximately 1 hour. I will be allowed to practice the procedure at my own pace until I feel confident with the series of events that I will be performing. The risks associated with using the walker apparatus are no greater than the use of any commercially available walkers that have been approved by the Assistive Devices Program of Ontario.

As a result of measuring the forces applied to a walker as people such as myself, the researchers hope to design a better parking brake system.

The information collected about me will remain strictly confidential and be identified by a code number and not by my name. All data for publication will be presented for the group, thereby eliminating the identification of individuals. All data will be securely stored in the Sunnybrook research office.

I understand that I am free to ask questions about the study at any time. I understand that my participation is voluntary and that I am free to withdraw or discontinue participation at any time and that participation in this study will not affect my current or future care at Sunnybrook Health Science Centre.

I have read the attached information sheet and the entire consent form and my questions about the study have been answered by the researcher.

I consent to participate in this study:

------------------------------	------------------------------	----------
print name of participant	signature of participant	date
------------------------------	------------------------------	----------
print name of witness	signature of witness	date

Appendix B - Modes of failure analysis programs

Appendix B.1

```
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'''''''''    DETERMINATION OF MINIMUM REQUIRED MASS TO ALLOW    '''''''
'''''''''                  A 5 CM SLIDE                         '''''''
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'''
''' This program is designed to evaluate the minimum required mass of
''' a walker that will avoid a 5 cm slide.  The program will evaluate
''' this weight for varying seat positions, center of gravity location
''' coefficients of friction, wheels bases, and configurations.
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Request variable ranges
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''


INPUT "Wheel base minimum:"; WheelBaseMin
INPUT "Wheel base maximum:"; WheelBaseMax
INPUT "Center of gravity minimum:"; CoGMin
INPUT "center of gravity maximum:"; CoGMax
INPUT "Trial minimum:"; TrialMin
INPUT "Trial maximum:"; TrialMax
INPUT "What maximum slipping distance is allowable (cm): "; SlipMax
INPUT "Friction Min: "; fMin
INPUT "Friction Max: "; fMax
INPUT "Minimum subject#: "; SubjMin
INPUT "Maximum subject#: "; SubjMax

Cutoff = .5

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Create loops to evaluate permutations of walker designs
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''


FOR f = fMin TO fMax STEP .2

FOR WheelBase = WheelBaseMin TO WheelBaseMax STEP 5

FOR CoG = CoGMin TO CoGMax STEP 10

FOR trial = TrialMin TO TrialMax

Subj$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SubjMin))), 3)
SlipMax$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SlipMax * 100))), 3)
Gravity$ = RIGHT$("00" + LTRIM$(RTRIM$(STR$(CoG))), 2)
Base$ = RIGHT$("00" + LTRIM$(RTRIM$(STR$(WheelBase))), 2)
f$ = RIGHT$("0" + LTRIM$(RTRIM$(STR$(f * 10))), 1)
b$ = RIGHT$("00" + LTRIM$(RTRIM$(STR$(WheelBase))), 2)
trial$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(trial))), 3)

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Open file for output and write the "Ratio" axis from -20 to 100
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''


OPEN "c:\joshua\data\sliding\wvsr\f" + f$ + "b" + b$ + "c" + Gravity$
```

```
PRINT #3, "Ratio",

FOR j = -20 TO 100

  IF j = 100 THEN
    PRINT #3, j
  ELSE PRINT #3, j,
  END IF

  j = j + 9

NEXT j


'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Begin testing same trial for each subject
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

FOR SubjNum = SubjMin TO SubjMax

SubjNum$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SubjNum))), 3)

g = 9.81
k = 44
DIM D(1502)
DIM SubjTot(1501)
DIM TA(1501)
DIM TB(1501)
DIM AShear(1501)
DIM BShear(1501)
ANorm = 0
BNorm = 0
CNorm = 0
WTemp = 0
Wmin = 0

D(1502) = 1000

PRINT #3, SubjNum,

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Read filtered data
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

OPEN "c:\joshua\data\filtered\trial" + SubjNum$ + "." + trial$ FOR INP


'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Record shear and normal forces for each point in time
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

FOR i = 1 TO 1501
   FOR g = 1 TO 6

     INPUT #1, j

     IF g = 2 THEN
       AShear(i) = j
     ELSEIF g = 3 THEN
```

```
    ANorm = j
   ELSEIF g = 4 THEN
    BShear(i) = j
   ELSEIF g = 5 THEN
    BNorm = j
   ELSEIF g = 6 THEN
    CNorm = j
   END IF

  NEXT g

''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Ignore data unless the applied force on the braked wheels is above
''' 0.5 Newtons
''''''''''''''''''''''''''''''''''''''''''''''''''''

  IF ANorm + BNorm < Cutoff THEN
   D(i) = 1000
  ELSE

''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine total applied force and location of force relative to
''' the braked wheels
'''''''''''''''''''''''''''''''''''''''''''''''''''''
   SubjTot(i) = ANorm + BNorm + CNorm

   TA(i) = ANorm / (ANorm + BNorm)
   TB(i) = BNorm / (ANorm + BNorm)

   X = (CNorm * k) / SubjTot(i)

   IF SubjNum = 532 OR SubjNum = 533 OR SubjNum = 535 OR SubjNum = 5
    HandlePosition = 1
   ELSE
    HandlePosition = 2
   END IF

   IF HandlePosition = 1 THEN
    IF trial < 5 THEN
     y = -5.6
    ELSEIF trial = 5 OR trial = 6 OR trial = 9 OR trial = 10 THEN
     y = -20
    ELSEIF trial = 7 OR trial = 8 OR trial = 11 OR trial = 12 THEN
     y = 12.4
    END IF
   ELSEIF HandlePosition = 2 THEN
    IF trial < 5 THEN
     y = -1.8
    ELSEIF trial = 5 OR trial = 6 OR trial = 9 OR trial = 10 THEN
     y = -16.2
    ELSEIF trial = 7 OR trial = 8 OR trial = 11 OR trial = 12 THEN
     y = 16.4
    END IF
   END IF

   D(i) = X - y

  END IF

NEXT i
```

```
CLOSE #1

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Create loop to evaluate required mass for range of seat positions
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

FOR Ratio = -20 TO 100

  PRINT , "Wheel base="; WheelBase
  PRINT , "Center of gravity="; CoG
  PRINT , "trial="; trial
  PRINT , "SubjNum="; SubjNum
  PRINT , "Ratio="; Ratio
  PRINT , ""

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Set high and low mass values as extremes for bisection
''' method
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
    W1 = 20
    W2 = 0

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Allow for up to 12 iterations
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

  FOR p = 1 TO 12

    dA = 0
    dB = 0
    distanceTempA = 0
    distanceTempB = 0
    distanceA = 0
    distanceB = 0

''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine if required mass is above or below the
''' average of the range
''''''''''''''''''''''''''''''''''''''''''''''''''''''''

    WTemp = (W1 + W2) / 2

    FOR i = 1 TO 1501

      IF D(i) <> 1000 THEN
        z = D(i) + ((Ratio / 100) * WheelBase)
        MomentCheck = (SubjTot(i) * (-z)) - (WTemp * g * WheelBase *
''''''''''''''Continued from line above:  CoG / 100)

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Calculate normal at each braked wheel
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
        IF MomentCheck > 0 THEN
          NormA = (TA(i) * SubjTot(i)) + ((WTemp / 2) * g)
          NormB = (TA(i) * SubjTot(i)) + ((WTemp / 2) * g)
        ELSE
          NormA = ((WTemp / 2) * g * WheelBase * (1 - (CoG / 100)) +
'''''''Continued:   TA(i) * SubjTot(i) * (WheelBase - z)) / WheelBase
          NormB = ((WTemp / 2) * g * WheelBase * (1 - (CoG / 100)) +
```

```
'''''''Continued:   TB(i) * SubjTot(i) * (WheelBase - z)) / WheelBase
         END IF

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine incremental distance the walker will move for
''' each data point for plate A
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

         IF (NormA > 0) AND (AShear(i) / (NormA) > f) THEN
           aA = (AShear(i) - (f * (NormA))) / (WTemp / 2)
           dA = .5 * aA * .02 * .02
         ELSEIF NormA <= 0 THEN
           aA = AShear(i) / (WTemp / 2)
           dA = .5 * aA * .02 * .02
         ELSE
           dA = 0
         END IF

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Sum incremental distances to determine total slide
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

         IF dA > 0 THEN
           distanceA = distanceA + dA
         END IF

      IF (D(i + 1) = 1000) AND (distanceA > distanceTempA) AND
''''''' Continued:  (distanceA <> 0) THEN
           distanceTempA = distanceA
           distanceA = 0
      END IF

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Reapeat the calculation for plate B
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

         IF (NormB > 0) AND (BShear(i) / (NormB) > f) THEN
           aB = (BShear(i) - (f * (NormB))) / (WTemp / 2)
           dB = .5 * aB * .02 * .02
        ELSEIF NormB <= 0 THEN
           aB = BShear(i) / (WTemp / 2)
           dB = .5 * aB * .02 * .02
         ELSE
           dB = 0
         END IF

         IF dB > 0 THEN
           distanceB = distanceB + dB
         END IF

     IF (D(i + 1) = 1000) AND (distanceB > distanceTempB) AND
''''''''''''' Continued:  (distanceB <> 0) THEN
           distanceTempB = distanceB
           distanceB = 0
     END IF
    END IF

    NEXT i

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
```

```
''' Define "distance" as the longest slide for the trial of
''' both wheels
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
     IF distanceTempA > distanceTempB THEN
       distance = distanceTempA * 100
     ELSE distance = distanceTempB * 100
     END IF

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Repeat iteration if the slide distance is not within 5%
''' of 5 cm
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

     IF p < 12 THEN
       IF ABS(distance - SlipMax) > (SlipMax * .05) THEN
         IF distance < SlipMax THEN
           W1 = WTemp
         ELSEIF distance > SlipMax THEN
           W2 = WTemp
         END IF
       ELSE
         Wmin = WTemp
         p = 12
       END IF
     ELSE Wmin = WTemp
         p = 12
     END IF
  NEXT p

  IF Wmin > 19.5 THEN
    Ratio = 100
  END IF

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Write required mass to a file
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

  IF Ratio = 100 THEN
    PRINT #3, Wmin
  ELSE
    PRINT #3, Wmin,
  END IF

  Ratio = Ratio + 9

NEXT Ratio
NEXT SubjNum
CLOSE
NEXT trial
NEXT CoG
NEXT WheelBase
NEXT f
END
```

Appendix B.2

```
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''''''   DETERMINATION OF MINIMUM REQUIRED MASS TO ALLOW A   ''''''''''
''''''                        2 CM TIP                       ''''''''''
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'''
''' This program is designed to evaluate the minimum required mass of
''' walker that will avoid a 2 cm rise of the braked wheels or the
''' front wheels.  The program will evaluate this mass for varying sea
''' positions,center of gravity loctions,wheel bases,and configuration
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Request variable ranges
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''


INPUT "Wheel base minimum:"; WheelBaseMin
INPUT "Wheel base maximum:"; WheelBaseMax
INPUT "Center of gravity minimum:"; CoGMin
INPUT "center of gravity maximum:"; CoGMax
INPUT "Trial minimum:"; TrialMin
INPUT "Trial maximum:"; TrialMax
INPUT "Minimum subject#: "; SubjMin
INPUT "Maximum subject#: "; SubjMax

Cutoff = 2

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Create loops to evaluate permutations of walker designs
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
FOR WheelBase = WheelBaseMin TO WheelBaseMax STEP 5

FOR CoG = CoGMin TO CoGMax STEP 10

FOR trial = TrialMin TO TrialMax

Subj$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SubjMin))), 3)
Gravity$ = RIGHT$("00" + LTRIM$(RTRIM$(STR$(CoG))), 2)
B$ = RIGHT$("00" + LTRIM$(RTRIM$(STR$(WheelBase))), 2)
trial$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(trial))), 3)

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Open file for output and write the "Ratio" axis from -20 to 50
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''


OPEN "c:\joshua\data\tipping\tables\b" + B$ + "c" + Gravity$ + "." + t

PRINT #3, "Ratio",

FOR j = -20 TO 50 STEP 10

  IF j = 50 THEN
    PRINT #3, j
  ELSE PRINT #3, j,
  END IF

NEXT j
```

```
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Begin testing same trial for each subject
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
FOR SubjNum = SubjMin TO SubjMax

SubjNum$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SubjNum))), 3)

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Define variables
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
DIM SubjTot(1501) '''Total Normal force applied by subject
DIM d(1502)
DIM ABSubj(1501)
DIM ABShear(1501)
DIM MomentMaxTemp(1501)
DIM MomentMinTemp(1501)
DIM dCoGB(1501)
DIM dCoGF(1501)
W = 0
g = 9.086
h = 10.2     '''Height of wheel axis above surface
AFz = 0      '''Plate A walker weight total over first "PointAvg" data
BFz = 0      '''Plate B walker weight total over first "PointAvg" data
CFz = 0      '''Plate C walker weight total over first "PointAvg" data
ABSubj = 0   '''Normal force of subject on plates (A + B)
CNorm = 0    '''Normal force of subject on plate C
x = 0        '''Fraction of wheelbase "SubjTot" acts from braked wheel
ABNorm = 0   '''Total resultant force at braked wheel
y = 0        '''Fraction of wheelbase of front seat edge to braked whee
z = 0        '''Range of values to test force over
k = 46       '''Wheel base of apparatus
PointAvg = 15 'Number of points at beginning of trial to average over
CoGHeight = 45

PRINT #3, SubjNum,

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Read filtered data
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

OPEN "c:\joshua\data\filtered\trial" + SubjNum$ + "." + trial$ FOR INP

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Record shear and normal forces for each point in time
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

FOR i = 1 TO 1501

  FOR p = 1 TO 6

     INPUT #1, j

     IF p = 2 THEN
        AShear = j
     ELSEIF p = 3 THEN
        ANorm = j
     ELSEIF p = 4 THEN
        BShear = j
     ELSEIF p = 5 THEN
```

```
         BNorm = j
      ELSEIF p = 6 THEN
         CNorm = j
      END IF

   NEXT p

   ABShear(i) = AShear + BShear
   ABSubj(i) = ANorm + BNorm
   SubjTot(i) = ABSubj(i) + CNorm

 ''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
 ''' Ignore data unless the applied force on the braked wheels is above
 ''' "cutoff" value
 ''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

   IF SubjTot(i) < Cutoff THEN

      d(i) = 1000

   ELSE
 ''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
 ''' Determine total applied force and location of force relative to
 ''' braked wheels
 ''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

      IF SubjNum = 532 OR SubjNum = 533 OR SubjNum = 535 OR SubjNum = 5
         HandlePosition = 1
      ELSE
         HandlePosition = 2
      END IF

      IF HandlePosition = 1 THEN
        IF trial < 5 THEN
          y = -5.6
        ELSEIF trial = 5 OR trial = 6 OR trial = 9 OR trial = 10 THEN
          y = -20
        ELSEIF trial = 7 OR trial = 8 OR trial = 11 OR trial = 12 THEN
          y = 12.4
        END IF
      ELSEIF HandlePosition = 2 THEN
        IF test < 5 THEN
          y = -1.8
        ELSEIF trial = 5 OR trial = 6 OR trial = 9 OR trial = 10 THEN
          y = -16.2
        ELSEIF trial = 7 OR trial = 8 OR trial = 11 OR trial = 12 THEN
          y = 16.4
        END IF
      END IF

      x = (CNorm * k) / SubjTot(i)
      d(i) = (x - y)
  END IF
NEXT i

CLOSE #15

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Create loop to evaluate required mass for range of seat positions
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
```

```
FOR Ratio = -20 TO 50 STEP 10

  PRINT , "wheelbase="; WheelBase
  PRINT , "center of gravity="; CoG
  PRINT , "trial="; trial
  PRINT , "SubjNum="; SubjNum
  PRINT , "Ratio="; Ratio
  PRINT , ""

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Seat high and low mass values as extremes for bisection method
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

  W1 = 20
  W2 = 0

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Allow for up to 12 iterations
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

  FOR p = 1 TO 12

    distance = 0
    dB = 0
    dF = 0
    distB = 0
    distF = 0
    distanceTempB = 0
    distanceTempF = 0
    distanceB = 0
    distanceF = 0
    dBLast = 0
    dFLast = 0
    A = 0
    B = 0

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine if required mass is above or below the average of range
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
    WTemp = (W1 + W2) / 2

    FOR i = 1 TO 1501
     IF d(i) <> 1000 THEN
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Calculate force, acceleration, and inctemental distance for rise
''' of the braked wheels
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

       CoGDistB = ((CoGHeight ^ 2) + ((WheelBase * (1 - CoG / 100))
''''''''' Continued:  ^ 2)) ^ .5
       z = ((Ratio / 100) * WheelBase) + d(i)
       MomentF = (((z - (h * ABShear(i) / SubjTot(i))) - WheelBase) *
''''' Continued: SubjTot(i)) - (WTemp * g * (100 - CoG) * WheelBase /
       ForceB = MomentF / CoGDistB
       aB = ForceB / (WTemp)
       dCoGB(i) = .5 * aB * .02 * .02
       dB = dCoGB(i) * WheelBase / CoGDistB
       IF dB > 0 THEN
          distanceB = distanceB + dB
       END IF
       IF dB <= 0 THEN
```

```
          A = 1
       END IF

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Total the distance that the wheels rise
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
       IF A = 1 THEN
         IF dBLast * dB < 0 OR i = 1500 THEN
          IF distanceB > distanceTempB THEN
           distanceTempB = distanceB
           distanceB = 0
          END IF
         END IF
       ELSE
         distanceTempB = distanceB
       END IF
       dBLast = dB

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Calculate force, acceleration, and inctemental distance for rise
''' of the free wheels
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

     CoGDistF = ((CoGHeight ^ 2) + (WheelBase * (CoG / 100) ^ 2)) ^ .5
     MomentB = (z * SubjTot(i)) + (WTemp * g * CoG * WheelBase / 100)
     ForceF = -MomentB / CoGDistF
     aF = ForceF / (WTemp)
     dCoGF(i) = .5 * aF * .02 * .02
     dF = dCoGF(i) * WheelBase / CoGDistF
     IF dF > 0 THEN
        distanceF = distanceF + dF
     END IF
     IF dF <= 0 THEN
       B = 1
     END IF

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Total the distance that the wheels rise
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
     IF B = 1 THEN
      IF dFLast * dF < 0 OR i = 1500 THEN
       IF distanceF > distanceTempF THEN
        distanceTempF = distanceF
        distanceF = 0
       END IF
      END IF
     ELSE
      distanceTempF = distanceF
     END IF

     dFLast = dF

   END IF
 NEXT i

'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine which of the free or braked wheels rose higher
'''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
 IF distanceTempF > distanceTempB THEN
    distance = distanceTempF * 100
```

```
 ELSE
    distance = distanceTempB * 100
 END IF

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Repeat iteration if the slide distance is not within 5% of 2 cm
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
 IF p < 12 THEN
   IF ABS(distance - 2) > (2 * .05) THEN
     IF distance < 2 THEN
       W1 = WTemp
     ELSEIF distance > 2 THEN
       W2 = WTemp
     END IF
   ELSE
     Wmin = WTemp
     p = 12
   END IF
 ELSE
   Wmin = WTemp
   p = 12
 END IF

PRINT , "WTemp="; WTemp
PRINT , "distance="; distance
PRINT , ""

NEXT p
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Write required mass to a file
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
IF Ratio = 50 THEN
   PRINT #3, Wmin
ELSE
   PRINT #3, Wmin,
END IF

NEXT Ratio
CLOSE #1
NEXT SubjNum
CLOSE
NEXT trial
NEXT CoG
NEXT WheelBase
END
```

Appendix B.3

```
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''''''''  DETERMINATION OF REQUIRED SHEAR TO ALLOW A 5 CM ROLL  ''''''
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'''
''' This program is designed to evaluate the minimum required shear of
''' the walker brakes that will avoid a 5 cm roll.
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Request variable ranges

INPUT "What maximum slipping distance is allowable (cm): "; SlipMax
INPUT "Minimum subject#: "; SubjMin
INPUT "Maximum subject#: "; SubjMax
INPUT "Min trial?"; trialmin
INPUT "Max trial?"; trialmax

Cutoff = 1

Subj$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SubjMin))), 3)
SlipMax$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SlipMax * 100))), 3)

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Create loop to examine all trials
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
FOR trial = trialmin TO trialmax

        IF trial = 1 OR trial = 2 THEN
           Config = 2
        ELSEIF trial = 3 OR trial = 4 THEN
           Config = 5
        ELSEIF trial = 5 OR trial = 6 THEN
           Config = 1
        ELSEIF trial = 7 OR trial = 8 THEN
           Config = 6
        ELSEIF trial = 9 OR trial = 10 THEN
           Config = 4
        ELSEIF trial = 11 OR trial = 12 THEN
           Config = 3
        END IF

trial$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(trial))), 3)
Config$ = RIGHT$("00" + LTRIM$(RTRIM$(STR$(Config))), 2)

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Open file for output and write the "Weight" axis from 1 to 20
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

IF trial = 1 OR trial = 3 OR trial = 5 OR trial = 7 OR trial = 9 OR tr
   OPEN "c:\joshua\data\rolling\roll.c" + Config$ FOR OUTPUT AS #3
END IF

PRINT #3, "Weight",

FOR j = 1 TO 20

  IF j = 20 THEN
```

```
    PRINT #3, j
  ELSE
    PRINT #3, j,
  END IF

NEXT j

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Begin testing the same trial for each subject for comparison
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

FOR SubjNum = SubjMin TO SubjMax

SubjNum$ = RIGHT$("000" + LTRIM$(RTRIM$(STR$(SubjNum))), 3)

g = 9.81
k = 44
DIM D(1501)
DIM SubjTot(1501)
DIM TA(1501)
DIM TB(1501)
DIM AShear(1501)
DIM BShear(1501)
ANorm = 0
BNorm = 0
CNorm = 0
ShearTemp = 0
ShearMin = 0

PRINT #3, SubjNum,

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Read filtered data
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
OPEN "c:\joshua\data\filtered\trial" + SubjNum$ + "." + trial$ FOR INP

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Record the shear at the braked wheels for each point in time
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

FOR i = 1 TO 1501
   FOR g = 1 TO 6

      INPUT #1, j

      IF g = 2 THEN
        AShear(i) = j
      ELSEIF g = 4 THEN
        BShear(i) = j
      END IF

   NEXT g

NEXT i

CLOSE #1

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Create loop to evaluate required shear for range of walker masses
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
```

```
FOR Weight = 1 TO 20

  PRINT , "trial="; trial
  PRINT , "SubjNum="; SubjNum
  PRINT , "Weight="; Weight

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Set high and low mass values as extremes for bisection method
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
  Shear1 = 200
  Shear2 = 0

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Allow for up to 12 iterations
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
  FOR p = 1 TO 12

    dA = 0
    dB = 0
    distanceTempA = 0
    distanceTempB = 0
    distanceA = 0
    distanceB = 0

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine if required shear is above or below average of range
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

    ShearTemp = (Shear1 + Shear2) / 2

     FOR i = 1 TO 1501

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine incremental acceleration and distance and sum for wheel
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

       IF AShear(i) > ShearTemp THEN
         aA = AShear(i) / (Weight / 2)
         dA = .5 * aA * .02 * .02
         IF dA > 0 THEN
           distanceA = distanceA + dA
         ELSE
           dA = 0
         END IF
       END IF
       IF (AShear(i) < .2) AND (distanceA > distanceTempA) AND
  ''''''''' Continued: (distanceA <> 0) THEN
         distanceTempA = distanceA
         distanceA = 0
       END IF

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine incremental acceleration and distance and sum for wheel
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

       IF BShear(i) > ShearTemp THEN
         aB = BShear(i) / (Weight / 2)
         dB = .5 * aB * .02 * .02
         IF dB > 0 THEN
           distanceB = distanceB + dB
```

```
         ELSE dB = 0
         END IF
       END IF
       IF (dB = 0) AND (distanceB > distanceTempB) AND (distanceB <> 0
         distanceTempB = distanceB
         distanceB = 0
       END IF

   NEXT i

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Determine which wheel has the greatest rolling distance
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

     IF distanceTempA > distanceTempB THEN
       distance = distanceTempA * 100
     ELSE distance = distanceTempB * 100
     END IF

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
'''Repeat iteration if the slide distance is not within 5% of 5 cm
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

   IF p < 12 THEN
     IF ABS(distance - SlipMax) > (SlipMax * .05) THEN
       IF distance < SlipMax THEN
         Shear1 = ShearTemp
       ELSEIF distance > SlipMax THEN
         Shear2 = ShearTemp
       END IF
     ELSE
       ShearMin = ShearTemp
       p = 12
     END IF
   ELSE ShearMin = ShearTemp
       p = 12
   END IF
NEXT p

''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''
''' Write required shear to file
''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''''

  IF Weight >= 20 THEN
    PRINT #3, ShearMin
  ELSE
    PRINT #3, ShearMin,
  END IF
NEXT Weight
NEXT SubjNum
IF trial = 2 OR trial = 4 OR trial = 6 OR trial = 8 OR trial = 10 OR t
   CLOSE #3
END IF
NEXT trial
CLOSE
END
```

Appendix C - Required design parameters

Configuration #1

$\mu = 0.4$

Wheel base = 35 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	+	+	+	+	+	+
	20	+	+	+	+	+	+	+	+
c/b	30	+	+	+	+	+	+	+	+
	40	+	+	+	+	+	+	+	+
	50	+	+	+	+	+	+	+	+
	60	+	+	+	+	+	+	+	+
	70	+	+	+	+	+	+	+	+

Wheel base = 50 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	18	18	+	+	+	+
	20	+	+	17	19	+	+	+	+
c/b	30	+	+	19	+	+	+	+	+
	40	+	19	+	+	+	+	+	+
	50	+	+	+	+	+	+	+	+
	60	+	+	+	+	+	+	+	+
	70	+	+	+	+	+	+	+	+

Wheel base = 40 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	19	+	+	+	+	+
	20	+	+	+	+	+	+	+	+
c/b	30	+	+	+	+	+	+	+	+
	40	+	+	+	+	+	+	+	+
	50	+	+	+	+	+	+	+	+
	60	+	+	+	+	+	+	+	+
	70	+	+	+	+	+	+	+	+

Wheel base = 55 cm

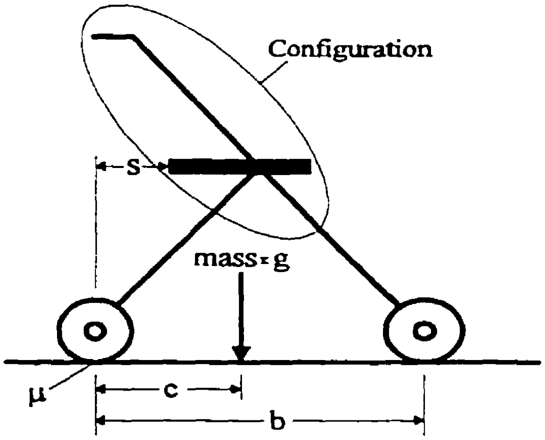
s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	18	16	19	+	+	+
	20	+	+	16	18	19	+	+	+
c/b	30	+	+	18	19	+	+	+	+
	40	+	19	19	+	+	+	+	+
	50	+	+	19	+	+	+	+	+
	60	+	+	+	+	+	+	+	+
	70	+	+	+	+	+	+	+	+

Wheel base = 45 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	18	19	+	+	+	+
	20	+	+	19	+	+	+	+	+
c/b	30	+	+	+	+	+	+	+	+
	40	+	+	+	+	+	+	+	+
	50	+	+	+	+	+	+	+	+
	60	+	+	+	+	+	+	+	+
	70	+	+	+	+	+	+	+	+



Configuration #1

$\mu = 0.8$

Wheel base = 35 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	19	+	+	+	+	+
20	+	+	+	+	+	+	+	+
30	+	+	+	+	+	+	+	+
40	+	19	+	+	+	+	+	+
50	+	+	+	+	+	+	+	+
60	+	+	+	+	+	+	+	+
70	+	+	+	+	+	+	+	+

Wheel base = 40 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	16	18	+	+	+	+
20	+	+	16	19	+	+	+	+
30	+	+	17	+	+	+	+	+
40	+	18	18	+	+	+	+	+
50	+	16	19	+	+	+	+	+
60	+	18	+	+	+	+	+	+
70	+	19	+	+	+	+	+	+

Wheel base = 45 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	18	15	18	+	+	+
20	+	+	13	16	18	+	+	+
30	+	+	14	16	19	+	+	+
40	+	19	15	18	+	+	+	+
50	+	16	16	19	+	+	+	+
60	+	14	17	+	+	+	+	+
70	+	16	19	+	+	+	+	+

Wheel base = 50 cm

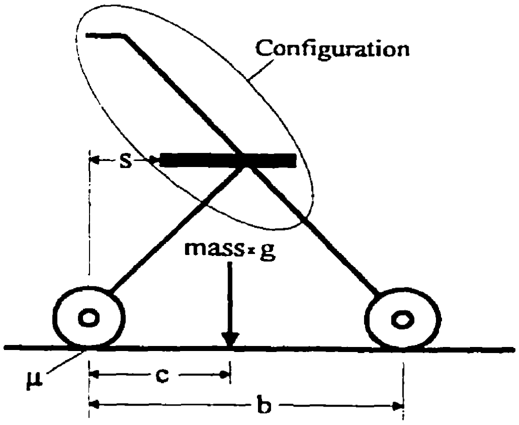
s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	18	13	15	18	+	+
20	+	+	12	13	16	19	+	+
30	+	+	11	14	16	19	+	+
40	+	19	12	15	18	+	+	+
50	+	16	13	16	19	+	+	+
60	+	14	14	18	+	+	+	+
70	+	14	16	19	+	+	+	+

Wheel base = 55 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	18	11	13	15	18	+
20	+	+	12	11	14	16	19	+
30	+	+	10	12	14	18	+	+
40	+	19	10	13	15	19	+	+
50	+	16	11	14	16	+	+	+
60	+	14	13	14	18	+	+	+
70	+	13	15	18	+	+	+	+



Configuration #2

$\mu = 0.4$

Wheel base = 35 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	13	14	15	16	18	19	+	+
20	14	15	16	18	19	+	+	+
30	15	16	18	19	+	+	+	+
40	16	18	19	+	+	+	+	+
50	18	19	+	+	+	+	+	+
60	19	+	+	+	+	+	+	+
70	+	+	+	+	+	+	+	+

Wheel base = 50 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	18	12	13	14	14	16	18	19
20	11	13	14	14	16	17	19	+
30	13	13	14	16	17	19	+	+
40	13	14	16	17	19	+	+	+
50	14	16	17	19	+	+	+	+
60	16	18	19	+	+	+	+	+
70	18	19	+	+	+	+	+	+

Wheel base = 40 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	12	13	14	15	16	18	19	+
20	13	14	15	16	18	19	+	+
30	14	15	16	18	19	+	+	+
40	15	16	18	19	+	+	+	+
50	16	18	19	+	+	+	+	+
60	18	19	+	+	+	+	+	+
70	19	+	+	+	+	+	+	+

Wheel base = 55 cm

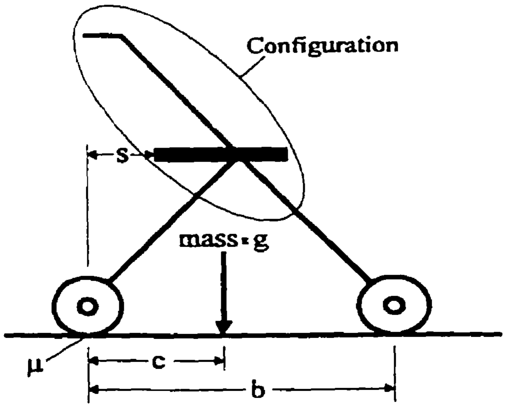
s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	11	12	13	14	16	17	18
20	15	12	13	14	15	16	18	19
30	12	13	14	15	16	18	19	+
40	13	14	15	16	18	19	+	+
50	14	15	16	18	19	+	+	+
60	15	16	18	19	+	+	+	+
70	16	19	+	19	+	+	+	+

Wheel base = 45 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	11	13	13	14	16	16	18	19
20	12	13	14	15	16	18	19	+
30	13	14	15	16	18	19	+	+
40	14	15	16	18	19	+	+	+
50	15	16	18	19	+	+	+	+
60	16	18	19	+	+	+	+	+
70	19	+	19	+	+	+	+	+



Configuration #2

$\mu = 0.8$

Wheel base = 35 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	7	8	9	11	12	13	14	18
	20	7	9	10	11	13	14	16	19
c/b	30	8	9	11	12	14	15	16	+
	40	8	10	12	13	15	16	18	+
	50	9	11	13	14	16	18	19	+
	60	11	13	14	16	19	+	+	+
	70	12	14	16	19	+	+	+	+

Wheel base = 40 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	6	7	8	9	10	12	13	15
	20	6	7	8	10	11	13	14	16
c/b	30	6	8	9	11	12	13	15	18
	40	7	8	10	11	13	14	16	19
	50	8	9	11	13	14	16	18	+
	60	8	10	12	14	16	18	+	+
	70	9	11	14	16	19	+	+	+

Wheel base = 45 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	10	5	7	8	9	10	12	13
	20	7	6	7	8	10	11	13	14
c/b	30	6	6	8	9	11	12	14	15
	40	5	7	8	10	12	13	15	17
	50	6	8	9	11	13	15	16	19
	60	7	9	11	13	14	16	19	+
	70	8	10	12	14	17	19	+	+

Wheel base = 50 cm

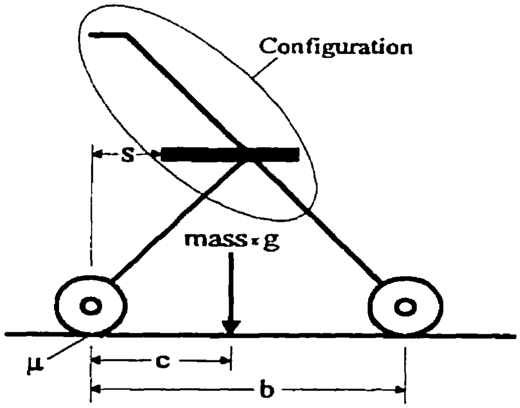
s/b

		-20	-10	0	10	20	30	40	50
	10	18	5	6	7	8	9	11	12
	20	11	5	6	8	9	10	12	13
c/b	30	8	5	7	8	10	11	13	14
	40	7	6	8	9	11	12	14	16
	50	6	7	8	10	12	14	15	18
	60	5	7	9	11	13	15	18	19
	70	6	8	11	13	15	18	+	19

Wheel base = 55 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	4	5	6	8	9	10	11
	20	15	4	6	7	8	9	11	12
c/b	30	11	5	6	8	9	10	12	13
	40	9	5	7	8	10	11	13	14
	50	8	6	7	9	11	13	14	16
	60	7	6	8	10	12	14	16	19
	70	6	7	9	11	14	16	19	+



Configuration #3

μ = 0.4

Wheel base = 35

s/b

c/b	-20	-10	0	10	20	30	40	50
10	13	8	8	10	12	15	+	+
20	8	8	9	11	13	16	+	+
30	8	9	9	11	14	17	+	+
40	9	9	10	13	15	+	+	+
50	9	10	11	13	16	+	+	+
60	10	11	11	14	18	+	+	+
70	11	11	13	16	+	+	+	+

Wheel base = 50

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	9	7	8	9	11	14	16
20	13	7	8	8	9	12	14	18
30	9	8	8	9	10	13	16	19
40	8	8	9	9	11	14	17	+
50	8	9	9	10	12	15	19	+
60	9	9	10	11	13	16	+	+
70	9	10	11	13	14	19	+	+

Wheel base = 40

s/b

c/b	-20	-10	0	10	20	30	40	50
10	13	8	8	9	11	13	16	+
20	8	8	8	9	11	14	17	+
30	8	8	9	10	13	15	18	+
40	8	9	9	11	13	16	19	+
50	9	9	10	11	14	18	+	+
60	9	10	11	13	16	19	+	+
70	10	11	12	14	18	+	+	+

Wheel base = 55

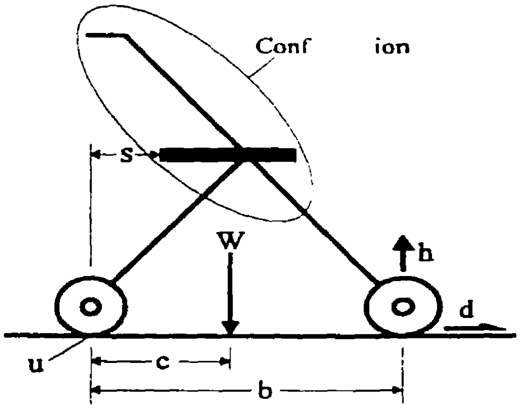
s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	10	7	8	8	10	13	15
20	19	7	8	8	9	11	14	16
30	13	8	8	9	9	12	15	18
40	10	8	9	9	10	13	16	19
50	8	8	9	10	11	14	18	+
60	8	9	10	11	12	15	19	+
70	9	10	11	12	13	18	+	+

Wheel base = 45

s/b

c/b	-20	-10	0	10	20	30	40	50
10	16	9	8	8	10	12	14	17
20	9	8	8	9	10	13	16	18
30	7	8	8	9	11	14	17	19
40	8	8	9	10	12	15	18	+
50	8	9	10	11	13	16	19	+
60	9	10	11	11	14	18	+	+
70	9	11	11	13	16	+	+	+



Configuration #3

$\mu = 0.8$

Wheel base = 35 cm

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	13	8	5	5	7	14	+	+
20	8	5	5	5	8	15	+	+
30	6	5	5	6	9	17	+	+
40	5	5	6	6	11	+	+	+
50	5	6	6	7	13	+	+	+
60	6	6	7	7	15	+	+	+
70	6	7	7	8	17	+	+	+

Wheel base = 40 cm

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	13	8	4	5	5	7	13	+
20	8	5	5	5	5	8	15	+
30	6	5	5	5	6	8	17	+
40	5	5	5	6	6	10	19	+
50	5	5	6	6	7	11	+	+
60	6	6	6	7	8	14	+	+
70	6	6	7	8	9	18	+	+

Wheel base = 45 cm

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	16	9	5	4	5	5	8	14
20	9	5	5	5	5	6	9	16
30	7	5	5	5	5	6	10	19
40	6	5	5	5	6	7	11	+
50	5	5	6	6	6	7	13	+
60	6	6	6	6	7	8	16	+
70	6	6	6	7	8	9	19	+

Wheel base = 50 cm

s/b

c/b

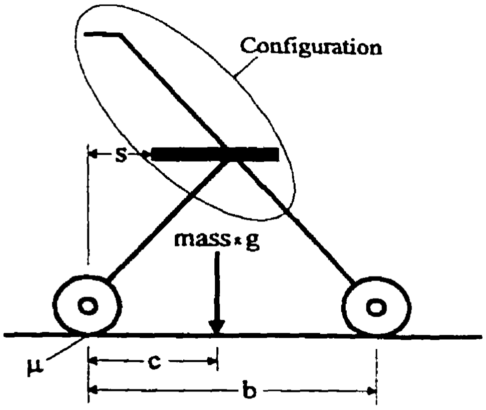
	-20	-10	0	10	20	30	40	50
10	+	9	5	4	5	5	6	10
20	13	5	5	5	5	5	7	11
30	9	5	5	5	5	6	8	13
40	8	5	5	5	6	6	8	15
50	6	5	5	6	6	7	9	18
60	5	6	6	6	7	8	9	+
70	6	6	6	7	8	9	10	+

Wheel base = 55 cm

s/b

c/b

	-20	-10	0	10	20	30	40	50
10	+	10	5	4	4	5	6	8
20	19	6	4	5	5	5	6	9
30	13	5	5	5	5	5	6	9
40	10	5	5	5	5	6	7	10
50	8	5	5	6	6	7	8	11
60	7	6	6	6	6	7	8	13
70	6	6	6	7	7	8	9	16



Configuration #4

μ = 0.4

Wheel base = 35 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	19	+	19	+	+	+
20	+	+	+	+	+	+	+	+
30	+	19	+	+	+	+	+	+
40	+	+	+	+	+	+	+	+
50	+	+	+	+	+	+	+	+
60	+	+	+	+	+	+	+	+
70	+	+	+	+	+	+	+	+

Wheel base = 50 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	11	13	16	18	+	+
20	+	+	12	14	16	19	+	+
30	+	19	13	15	18	+	+	+
40	+	15	14	16	19	+	+	+
50	+	13	15	18	+	+	+	+
60	+	13	16	19	+	+	+	+
70	18	14	18	+	+	+	+	+

Wheel base = 40 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	16	18	+	+	+	+
20	+	+	17	19	+	+	+	+
30	+	16	18	+	+	+	+	+
40	+	17	19	+	+	+	+	+
50	+	18	+	+	+	+	+	+
60	+	19	+	+	+	+	+	+
70	19	+	+	+	+	+	+	+

Wheel base = 55 cm

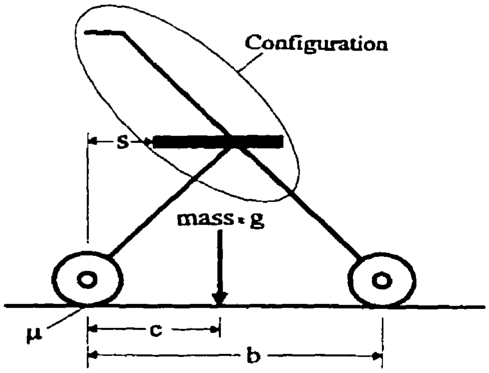
s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	9	12	14	16	18	+
20	+	+	10	13	14	17	19	+
30	+	19	11	13	16	18	+	+
40	+	15	12	14	17	19	+	+
50	+	13	13	15	19	+	+	+
60	+	11	14	16	19	+	+	+
70	18	13	15	19	+	+	+	+

Wheel base = 45 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	13	15	18	+	+	+
20	+	+	14	16	19	+	+	+
30	+	17	15	18	+	+	+	+
40	+	14	16	19	+	+	+	+
50	+	15	18	+	+	+	+	+
60	+	16	19	+	+	+	+	+
70	18	18	+	+	+	+	+	+



Configuration #4
$\mu = 0.8$

Wheel base = 35 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	16	18	+	18	+	+
20	+	+	17	19	+	19	+	+
30	+	16	18	+	+	+	+	+
40	+	17	19	+	+	+	+	+
50	+	19	+	+	+	+	+	+
60	19	+	+	+	+	+	+	+
70	19	+	+	+	+	+	+	+

Wheel base = 50 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	6	9	11	14	16	19
20	+	+	7	9	12	15	18	+
30	+	19	7	10	13	16	19	+
40	+	15	8	11	14	18	+	+
50	+	13	9	13	16	19	+	+
60	+	11	10	14	18	+	+	+
70	18	10	11	16	+	+	+	+

Wheel base = 40 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	12	14	17	19	+	+
20	+	+	13	16	18	+	+	+
30	+	16	14	17	19	+	+	+
40	+	13	15	18	+	+	+	+
50	+	13	17	+	+	+	+	+
60	+	15	19	+	+	+	+	+
70	17	17	+	+	+	+	+	+

Wheel base = 55 cm

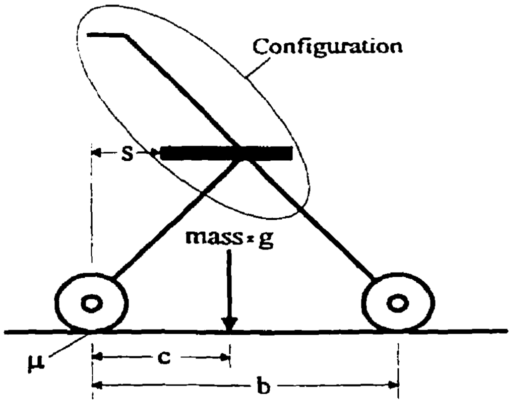
s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	6	7	9	12	14	17
20	+	+	6	7	10	13	16	18
30	+	19	6	8	11	14	17	+
40	+	15	7	8	12	15	19	+
50	+	13	7	9	13	17	+	+
60	+	11	8	11	15	19	+	+
70	18	10	9	12	17	+	+	+

Wheel base = 45 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	+	+	9	11	14	16	19	+
20	+	+	9	12	15	18	+	+
30	+	17	10	13	16	19	+	+
40	+	14	11	14	18	+	+	+
50	+	12	13	16	19	+	+	+
60	+	10	14	18	+	+	+	+
70	18	11	16	+	+	+	+	+



Configuration #5

$\mu = 0.4$

Wheel base = 35 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	13	14	16	18	19	+	+	+
20	14	16	17	19	+	+	+	+
30	15	16	18	+	+	+	+	+
40	16	18	19	+	+	+	+	+
50	18	19	+	+	+	+	+	+
60	19	+	+	+	+	+	+	+
70	+	+	+	+	+	+	+	+

Wheel base = 40 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	11	13	14	16	17	19	+	+
20	12	14	15	17	18	+	+	+
30	13	14	16	18	19	+	+	+
40	14	16	18	19	+	+	+	+
50	15	18	19	+	+	+	+	+
60	16	19	+	+	+	+	+	+
70	19	+	+	+	+	+	+	+

Wheel base = 45 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	10	11	13	14	16	18	19	+
20	11	13	14	15	17	18	+	+
30	11	13	15	16	18	19	+	+
40	13	14	16	18	19	+	+	+
50	14	15	18	19	+	+	+	+
60	15	17	19	+	+	+	+	+
70	16	19	+	+	+	+	+	+

Wheel base = 50 cm

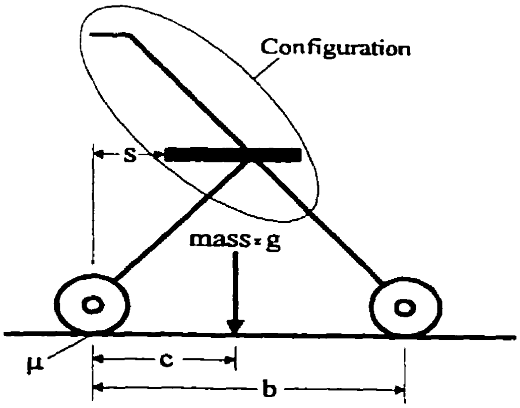
s/b

c/b	-20	-10	0	10	20	30	40	50
10	9	11	12	13	14	16	18	+
20	10	11	13	14	16	18	19	+
30	10	12	14	15	17	19	+	+
40	11	13	14	16	18	+	+	+
50	12	14	16	18	19	+	+	+
60	13	15	18	19	+	+	+	+
70	14	17	19	+	+	+	+	+

Wheel base = 55 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	8	10	11	13	14	15	17	19
20	9	10	12	13	14	16	18	+
30	9	11	13	14	16	18	19	+
40	10	12	14	15	17	19	+	+
50	11	13	14	16	19	+	+	+
60	12	14	16	18	+	+	+	+
70	13	15	18	+	+	+	+	+



Configuration #5

$\mu = 0.8$

Wheel base = 35 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	7	9	10	12	14	16	+	+
20	8	9	11	13	15	17	+	+
30	8	10	12	14	16	19	+	+
40	9	11	13	16	18	+	+	+
50	10	13	15	18	+	+	+	+
60	11	14	17	19	+	+	+	+
70	13	16	19	+	+	+	+	+

Wheel base = 50 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	8	6	5	7	9	10	12	14
20	5	4	6	8	9	11	13	15
30	4	5	6	8	10	12	14	16
40	3	5	7	9	11	13	16	18
50	3	5	8	10	13	15	18	+
60	4	6	8	11	14	17	+	+
70	4	7	9	13	16	19	+	+

Wheel base = 40 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	6	7	8	10	12	13	16	+
20	6	7	9	11	13	14	17	+
30	6	8	10	12	14	16	19	+
40	7	9	11	13	15	18	+	+
50	7	9	12	14	17	19	+	+
60	8	11	13	16	19	+	+	+
70	9	12	15	19	+	+	+	+

Wheel base = 55 cm

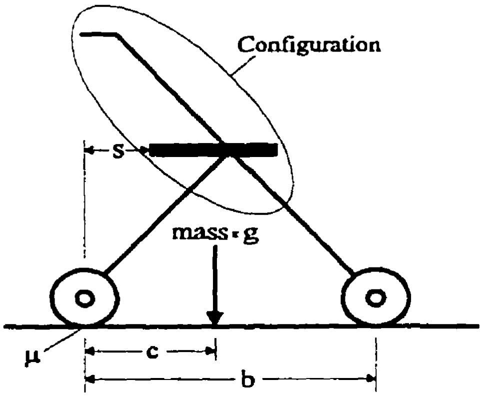
s/b

c/b	-20	-10	0	10	20	30	40	50
10	8	6	5	6	8	9	11	13
20	5	4	5	7	8	10	12	14
30	4	3	5	7	9	11	13	15
40	3	4	6	8	10	12	14	17
50	3	4	6	8	11	13	16	19
60	3	5	7	9	12	15	18	+
70	3	5	8	11	14	18	+	+

Wheel base = 45 cm

s/b

c/b	-20	-10	0	10	20	30	40	50
10	7	6	7	8	10	12	14	17
20	5	6	7	9	11	13	15	18
30	4	6	8	10	12	14	16	19
40	5	7	9	11	13	15	18	+
50	5	7	9	12	14	17	19	+
60	6	8	11	13	16	19	+	+
70	6	9	12	15	19	+	+	+



Configuration #6

$\mu = 0.4$

Wheel base = 35 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	16	18	+	+	+	+
	20	18	14	17	19	+	+	+	+
c/b	30	14	16	19	+	+	+	+	+
	40	14	18	+	+	+	+	+	+
	50	16	19	+	+	+	+	+	+
	60	18	+	+	+	+	+	+	+
	70	+	+	+	+	+	+	+	+

Wheel base = 40 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	14	17	19	+	+	+
	20	19	13	15	18	+	+	+	+
c/b	30	14	14	17	19	+	+	+	+
	40	12	15	19	+	+	+	+	+
	50	14	17	+	+	+	+	+	+
	60	16	19	+	+	+	+	+	+
	70	18	+	+	+	+	+	+	+

Wheel base = 45 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	13	15	18	+	+	+
	20	19	13	14	17	19	+	+	+
c/b	30	14	13	15	18	+	+	+	+
	40	12	14	17	+	+	+	+	+
	50	12	16	19	+	+	+	+	+
	60	14	18	+	+	+	+	+	+
	70	16	+	+	+	+	+	+	+

Wheel base = 50 cm

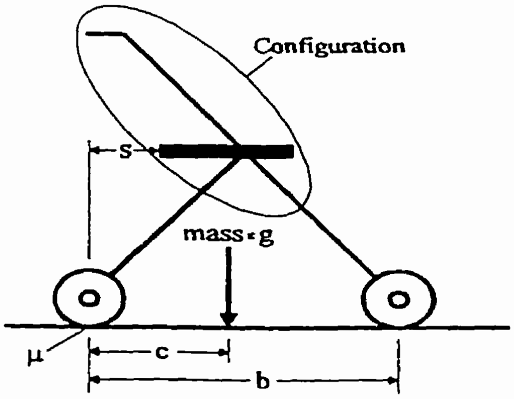
s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	12	14	17	19	+	+
	20	+	13	13	16	18	+	+	+
c/b	30	15	11	14	17	+	+	+	+
	40	12	13	16	19	+	+	+	+
	50	11	14	18	+	+	+	+	+
	60	13	16	+	+	+	+	+	+
	70	14	19	+	+	+	+	+	+

Wheel base = 55 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	11	14	16	19	+	+
	20	+	13	12	15	18	+	+	+
c/b	30	15	11	13	16	19	+	+	+
	40	12	12	15	18	+	+	+	+
	50	10	13	16	+	+	+	+	+
	60	11	15	19	+	+	+	+	+
	70	13	18	+	+	+	+	+	+



Configuration #6

$\mu = 0.8$

Wheel base = 35 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	13	5	8	11	17	+
	20	18	13	8	6	9	12	19	+
c/b	30	14	10	6	7	10	13	+	+
	40	11	8	6	7	11	15	+	+
	50	10	7	6	8	12	17	+	+
	60	8	6	6	9	14	+	+	+
	70	8	7	7	11	18	+	+	+

Whee base = 50 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	12	5	5	6	9	12
	20	+	13	7	5	5	7	10	13
c/b	30	15	10	6	5	5	8	11	15
	40	12	8	5	5	6	9	13	17
	50	10	7	6	6	6	10	14	19
	60	9	6	6	6	7	12	17	+
	70	8	6	6	7	8	14	+	+

Wheel base = 40 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	13	5	6	9	12	17
	20	19	13	7	5	7	10	13	19
c/b	30	14	10	6	5	8	11	14	+
	40	12	8	5	6	8	12	16	+
	50	10	7	6	6	9	14	18	+
	60	8	6	6	7	11	16	+	+
	70	8	6	7	8	13	19	+	+

Wheel base = 55 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	11	5	5	5	8	11
	20	+	13	7	5	5	6	9	12
c/b	30	15	10	6	5	5	7	10	14
	40	12	8	5	5	5	8	11	15
	50	10	7	6	6	6	9	13	18
	60	9	6	6	6	6	10	15	+
	70	8	6	6	6	7	12	19	+

Wheel base = 45 cm

s/b

		-20	-10	0	10	20	30	40	50
	10	+	+	13	5	5	7	10	13
	20	19	13	7	5	5	8	11	15
c/b	30	14	10	6	5	6	9	13	16
	40	12	8	5	5	7	10	14	18
	50	10	7	6	6	8	12	16	+
	60	9	6	6	6	9	14	19	+
	70	8	6	6	7	10	17	+	+

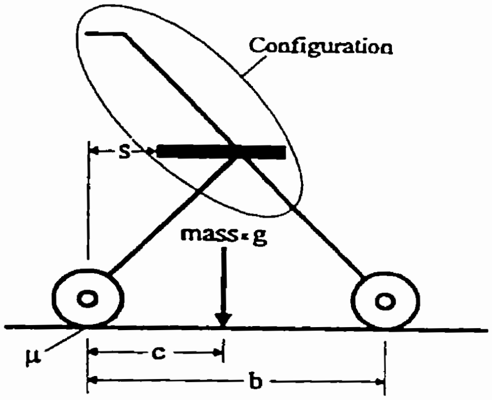


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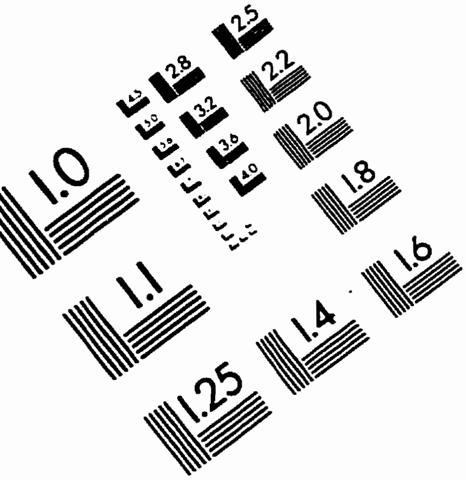
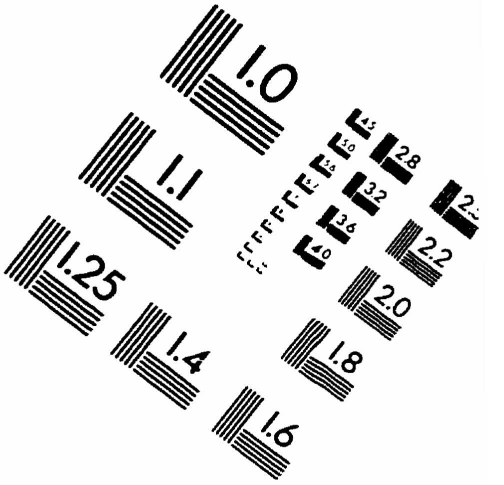
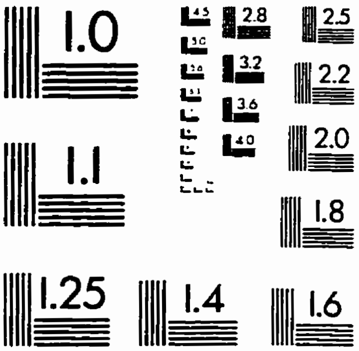
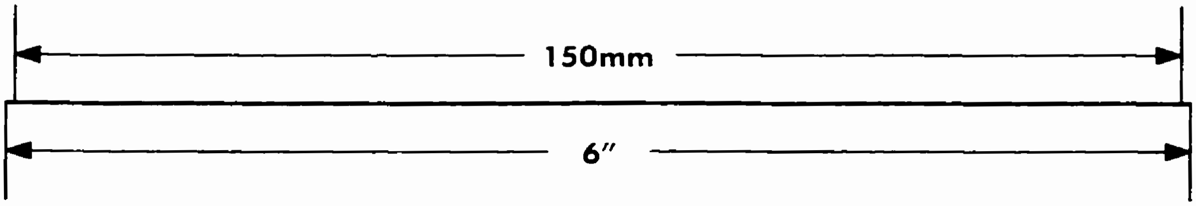
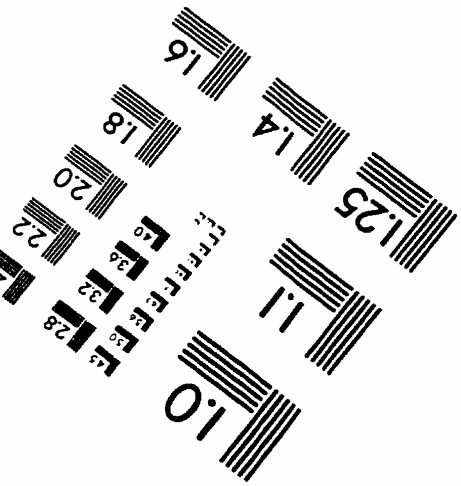
IMAGE EVALUATION TEST TARGET (QA-3)











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