

Racing wheelchair crown compensation

Rory A. Cooper, MEng

Institute of Environmental Stress Human Performance Lab, and the Control Systems Lab, Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106

Abstract—This paper is concerned with the directional stability of racing wheelchairs on crown roads. Three types of crown compensators are described and evaluated: the push-pull, the push-push, and the pull-pull. It was found that the push-push and the push-pull types of compensators have the most desirable characteristics, and were, in general, safer than the pull-pull type. In addition, the equations necessary to specify the minimum spring force required to compensate for the downhill turning moment, were derived and compared to the actual preset forces for the various compensators presently in use. It was found that the force required to maintain directional stability was less than that to deflect the crown compensator. This was due to the preference of athletes for additional stiffness needed for disturbance rejection, and to help compensate for any asymmetry in their stroke kinematics. It was also more cost-effective for the manufacturer to build stiffer-than-necessary crown compensators so that a range of individual and racing wheelchair combinations could use the same crown compensator.

Key words: *center of gravity, crown compensators, directional instability, racing wheelchairs.*

INTRODUCTION

Wheelchair racing, the sport of propelling a wheelchair with push-rings over a predesignated

course in a minimum amount of time, is an important aspect of the rehabilitation of many spinal cord injured patients (6). The increased popularity of this sport has prompted athletes and manufacturers to develop improvements in wheelchairs. These wheelchairs (**Figure 1**) have several distinguishing features, such as tubular tires, light-weight rims, precision hubs, larger wheels, and smaller push-rings.

Although racing wheelchairs have some of the same control problems as everyday wheelchairs, these problems are amplified due to the speeds (in excess of 40 mph on down grades) attainable by elite wheelchair athletes. Several factors affect racing wheelchair propulsion: weight, materials, design and physical dimensions of the racing wheelchair; level of fitness, strength, and ability of the athlete; compatibility of the racing wheelchair and the athlete, along with external factors such as the texture, hardness, and crown of the road. Significant efforts have been made by a number of investigators to classify and quantify these relationships (2,3,4,7,8). There is still a substantial amount of investigation required, especially in the analysis of wheelchair racing. The interaction of many factors involved in wheelchair racing performance makes it difficult to change a single variable without affecting other variables.

One problem that is of great significance is the downhill turning moment induced by road crown. In wheelchair racing, differential pushing or inducing a drag on the rear wheel are not acceptable, because

Address all correspondence to: Rory A. Cooper, M.Eng., Department of Electrical and Computer Engineering, University of California, Santa Barbara, CA 93106.

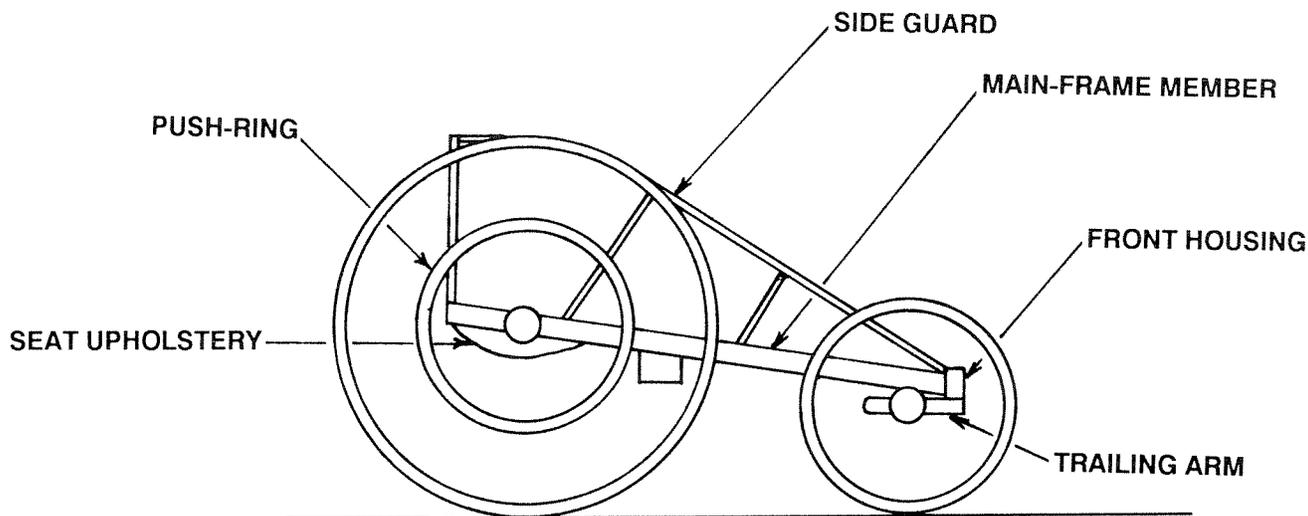


Figure 1.
Racing wheelchair.

of the increased energy requirements or the decreased speed (1).

PROBLEM DEFINITION

The purpose of this investigation was to analyze the factors that have an effect on the directional stability of racing wheelchairs on crowned roads (**Figure 2**), and to develop the relationships necessary for satisfactorily controlling the direction.

METHODS

Racing wheelchairs do not require the maneuverability of everyday wheelchairs, because their purpose is to proceed in a forward direction as rapidly as possible under human power, using push-rings for propulsion. A spring-loaded device attached to a front wheel assembly can be used to compensate for directional instability.

Three experienced spinal cord injured wheelchair racers, using racing wheelchairs modified to accept three types of crown compensator mechanisms, evaluated the properties of each crown compensator type. They evaluated each compensator mechanism after training with each one for a minimum of 14 days, over various types of courses with differing degrees of road crown. Each individual was then interviewed.

FUNCTION

The crown compensator functions by exerting a force on the fork or trailing arm of the front wheel opposing the force due to road crown. The three types tested are described below.

Pull-pull compensator

The springs of the pull-pull compensator are in tension with equal, but opposite, forces when there is no displacement of the tie-rod assembly. It functions by exerting a force on the tie-rod arms opposite to the displacement. (The force is due to the extension of one of the springs.) The compensator lever is attached to the center of the front crossmember by a hinge (which has a high degree of resistance); this lever is used to set the desired direction, i.e., the zero position of the springs. The orientation of the pull-pull compensator is illustrated in **Figure 3a** and **Figure 3b**.

Push-push compensator

The casing of the push-push compensator is fixed to one of the main frame members, while the shaft is affixed to the fork or trailing arm. The spring encased in the compensator mechanism is compressed when the front wheels are moved from the zero position, thus generating a force to return the wheels. The spring may be preloaded to prevent movement due to small forces. The orientation of

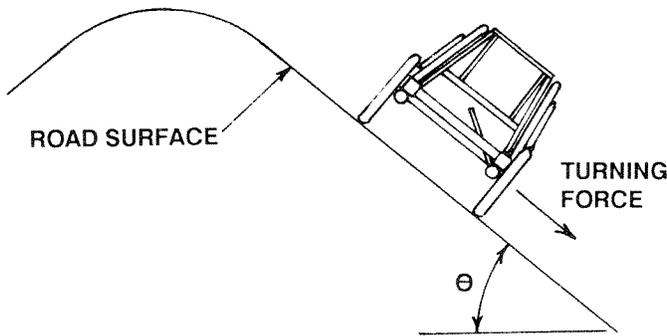


Figure 2.
Racing wheelchair on crowned road.

the push-push compensator is depicted in **Figure 4a**, and in greater detail in **Figure 4b**.

Push-pull compensator

The orientation of the push-pull compensator is shown in **Figure 5a**, and the mechanism is shown in **Figure 5b**. It is affixed to a lever at one end, and to the fork or trailing arm at the other end. (The lever is resistive to movement, so that there is no change in position of the lever due to forces acting on the front wheels.) When a force acting upon the front wheels causes a displacement, one of the springs is in compression while the other is in tension, thus generating a force in opposition to the displacement.

The springs can be preloaded to prevent movement for small forces at the wheels.

As can be seen in **Figure 3a**, **Figure 4a**, and **Figure 5a**, the steering lever(s) are rigidly attached to the trailing arm(s) of the front wheel(s). This requires the individual to overcome the force of the crown compensator when making voluntary directional changes.

The forces required for initial compression and for maximal compression for typical crown compensator mechanisms were measured using an Arbor press equipped with a load cell. (**Table 1**).

Table 1.
Crown compensator mechanism spring forces.

	SPRING FORCE	
	minimum	maximum
Ray Stewart Self-Centering Compensator (Push-Push)	20 lbs. 89 N	40 lbs. 178 N
Bob Hall Crown Compensator (light) (Push-Pull)	30 lbs. 133 N	50 lbs. 222 N
(heavy)	35 lbs. 156 N	55 lbs. 245 N
Typical Pull-Pull Spring Compensator	5 lbs. 22 N	20 lbs. 89 N



Figure 3a.
View of the front end of a racing wheelchair with a pull-pull compensator. (a. front wheel, b. tie-rod, c. compensator lever, d. steering lever, e. compensator, f. tie-rod arm [stand-off]).

STATIC ANALYSIS

A theoretical static analysis was done to develop a method for therapists and manufacturers to determine the proper crown compensator setting for each athlete.

The slope created by road crown for water drainage generates a downhill turning moment. This results from the mass distribution of a racing wheelchair and athlete relative to the wheel orientation (**Figure 6a**).

The downhill turning moment about the rear wheel is a consequence of the center of gravity being located in front of the rear axles. The force which creates the turning moment is depicted in **Figure 6b**.

M is the mass of the athlete and racing wheelchair, g is the acceleration due to gravity (9.81m/s^2), θ is the angle created by the road crown. The forces required for crown compensation by the use of a spring compensator mechanism attached to the front wheel assembly are depicted in **Figure 6c**.

F_{spring} is the force required to compensate for the turning moment of the front wheels about the front spindles; F_{reaction} is the force on the front wheels acting against the road surface; L is the distance of the center of gravity of the athlete-racing wheelchair system to the rear axle intersection of the

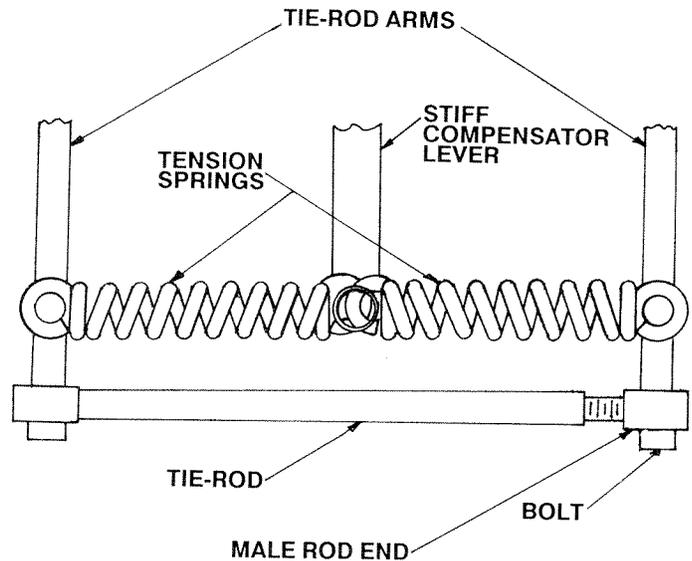


Figure 3b.
Pull-pull crown compensator mechanism.

center line; l is the distance of the crown compensator mechanism point of attachment to the front wheel spindle; and T is the trail of the front wheel.

To determine the required spring tension for the crown compensator, the moments about the front wheel spindle must be summed.



Figure 4a.
View of the front end of a racing wheelchair with a push-pull compensator. (a. front wheel, b. tie-rod, d. steering lever, e. compensator, f. tie-rod arm [stand off]).

$$F_{\text{reaction}} (T) = F_{\text{spring}} (l)$$

The moments about the downhill rear wheel, the pivot point, must also be summed.

$$F_{\text{reaction}} (\text{WHEELBASE}) = MgL\sin\theta$$

Now solving for F_{spring}

$$F_{\text{spring}} (l/T) = F_{\text{reaction}}$$

$$F_{\text{spring}} (l/T) \text{ WHEELBASE} = MgL\sin\theta$$

$$F_{\text{spring}} = MgLT\sin\theta / l (\text{WHEELBASE})$$

Thus, the crown compensator spring force must be preset to a force equal to or greater than the calculated value for static directional stability.

A method for determining the location of the center gravity for the athlete and racing wheelchair is depicted in **Figure 7** (5).

The center of gravity can be calculated by using the linear relationship between the position of the center of gravity as follows:

$$\text{when } y = z \text{ then } F = W$$

$$\text{thus } F = W (y / z) \text{ and } y = x + L$$

$$\text{and } y = (z / W) F$$

$$\text{therefore } F (z / W) = x + L$$

$$\text{so } L = F (z / W) - x$$

Where F is the value of the load cell or scale force, z is the distance from the center of the fulcrum to the point where the platform touches the load cell or scale; W is the combined weight of the athlete and racing wheelchair; and, x is the distance from the point where the rear wheels touch the platform to the center of the fulcrum.

An athlete and racing wheelchair weighing 622.7 N (140 pounds) were tested to determine the proper crown compensator spring force for an angle of 10 degrees (the maximum angle one might expect

to encounter), using the equations derived in the static analysis. The racing wheelchair had a trail of 7.62 cm (3 inches), the crown compensator was attached 5.08 cm (2 inches) from the spindle, and the wheelbase was 68.58 cm (27 inches).

The distance of the center of gravity from the rear axles must first be found. In this case the platform length (z) was 2 m, the distance from the fulcrum to the rear axles (x) was 30 cm, and F was measured to be 135 N (30.4 pounds).

Thus:

$$L = 135 \text{ N} (200 \text{ cm} / 622.7 \text{ N}) - 30 \text{ cm} = 13.36 \text{ cm}$$

The distance of the center of gravity from the rear axles is 13.36 cm. The compensator spring force required (F_{spring}) is as follows:

$$F_{\text{spring}} = \frac{(622.7 \text{ N}) (\sin(10)) (13.36 \text{ cm}) (7.62 \text{ cm})}{(5.08 \text{ cm}) (68.58 \text{ cm})} = 31.6 \text{ N}$$

Thus, the force for initial movement for the crown compensator must be at least as great as 31.6 N (7.1 pounds).

RESULTS

The three athletes made the following observations about the characteristics of the three types of crown compensator mechanisms:

The pull-pull crown compensator was determined to be the least desirable, as it required the greatest amount of adjusting for changes in the road crown, and it had the most difficulty tracking. This is probably due to the negating effect of the opposing tension of each spring, which translates to small reaction forces for small perturbations. In addition to these problems, the pull-pull crown compensator is, in the event of failure, not self-centering. When a spring breaks, or otherwise becomes detached, the front wheels rapidly turn to the side, which can cause injuries.

The push-push crown compensator and the push-pull crown compensator have nearly equal handling characteristics. Their designs allow the springs to be preloaded to prevent most movement due to directional instability or external disturbances. Both of these crown compensators are self-centering, thus avoiding the problem of abrupt directional changes because of crown compensator failure. No force is exerted on the wheel assembly in

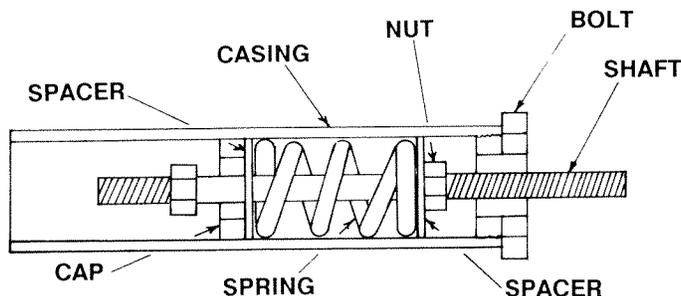


Figure 4b.
Push-push crown compensator mechanism.

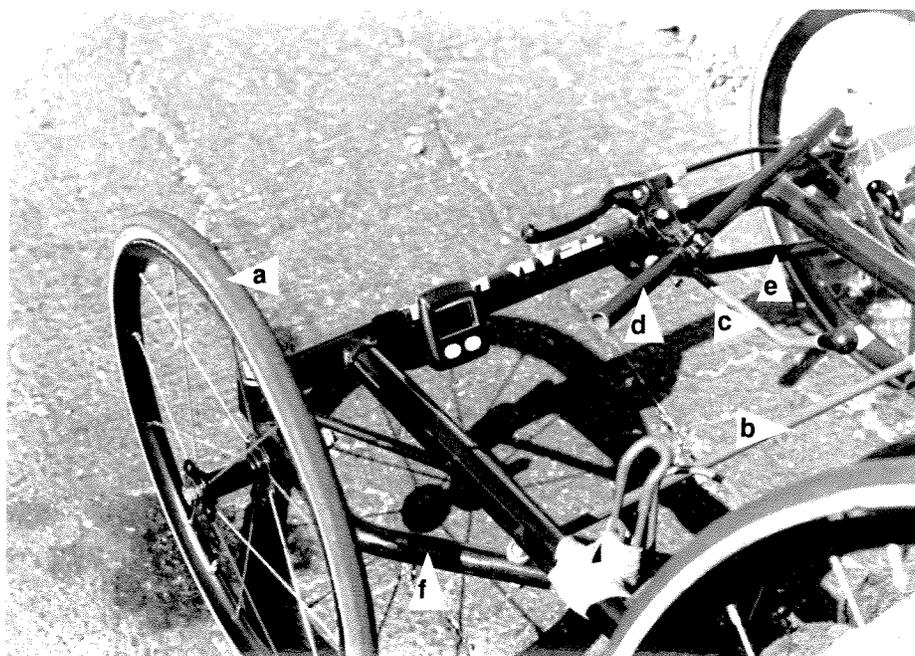


Figure 5a.
View of the front end of a racing wheelchair with a push-pull compensator. (a. front wheel, b. tie-rod, c. compensator lever, d. steering lever, e. compensator, f. tie-rod arm [stand off]).

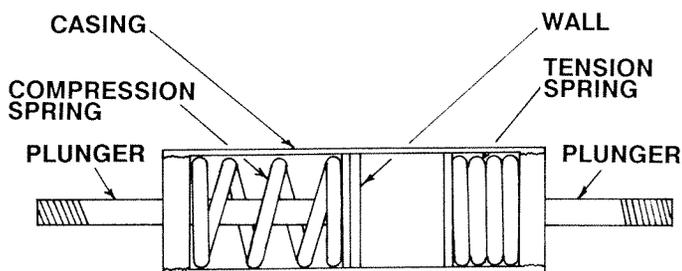


Figure 5b.
Push-pull crown compensator mechanism.

the absence of road crown reducing the stress on the front wheel assemblies, making alignment of the front wheels simpler. The only undesirable characteristic noted seems to be some internal binding that makes accurate control less than optimal while voluntarily turning.

The crown compensator force is limited by the ability of the athlete to overpower the crown compensator when voluntarily making directional changes. This is of special concern to quadriplegic athletes because of their reduced arm strength and dexterity.

DISCUSSION

The problem of the downhill turning moment has been investigated, and three methods of controlling the racing wheelchair direction were evaluated. Crown compensation mechanisms appear to satisfactorily solve most of the directional instability problems induced by road crown and small disturbances. The pull-pull crown compensator mechanism, though widely used for racing, was the least desirable of the mechanisms evaluated, and for reasons of safety, not to be recommended. The push-pull crown compensator mechanism would initially seem to be the best for road racing and track competition; however, the push-push crown compensator works equally as well on the road.

A static analysis of the road crown directional stability problem was performed, and equations were developed to help therapists and manufacturers select the proper compensator for each athlete. The best results were obtained when the center of gravity measurements were made with the athlete's chest resting on his/her knees, and with his/her arms hanging to the side.

Admittedly, the sample size for this study was small, and the results based upon their evaluations may thus be biased. Small sample size is a common

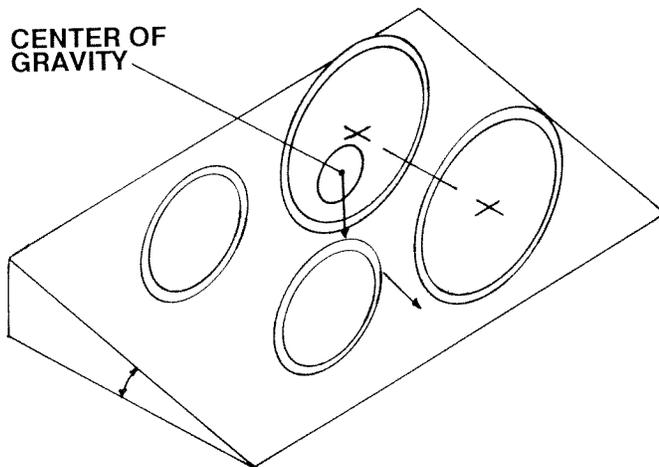


Figure 6a.
Downhill turning moment.

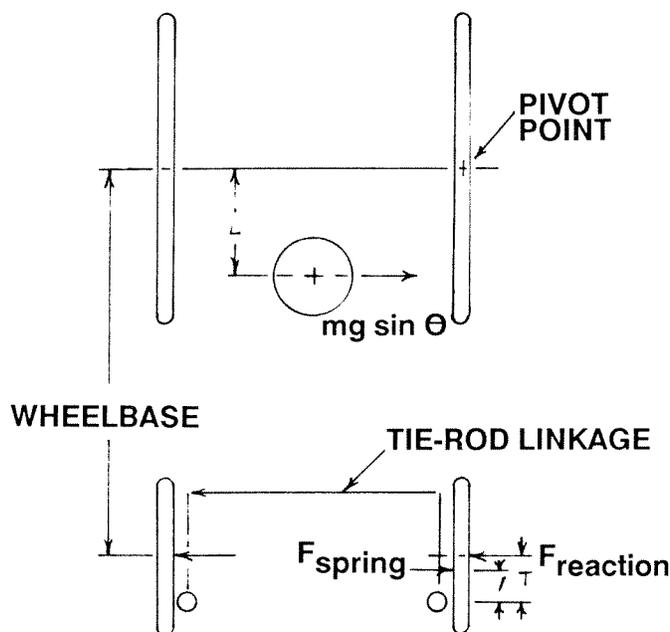


Figure 6c.
Compensation analysis.

problem when evaluating rehabilitation research; however, by using experienced spinal cord injured wheelchair racing athletes (who are very familiar with the performance of their racing wheelchairs), the validity of these results should be greater than for a comparable random sample.

The results of the static analysis indicate that the forces required to compensate for road crown

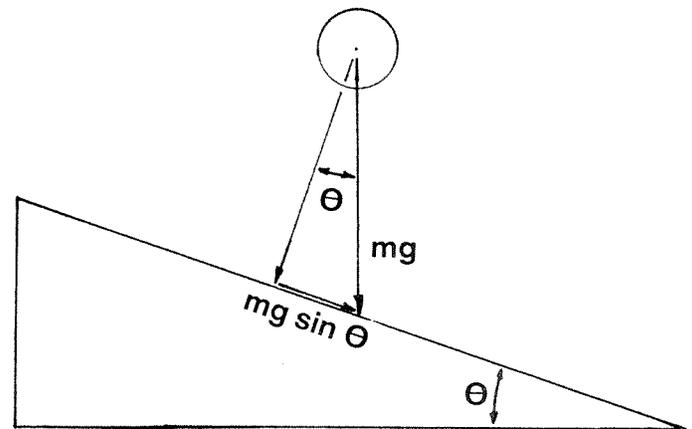


Figure 6b.
Distribution of forces.

are 2 to 4 times less than the initial compression force for the sample push-push and push-pull compensator mechanisms. These crown compensators are constructed to function satisfactorily for a number of individuals of various weights. In addition, wheelchair athletes prefer the added stiffness that results, and the greater force helps to compensate for any asymmetry in the athlete's stroke (due to dominant side or on the occasion of missing a stroke with one arm).

Special care must be taken to insure that the steering levers are properly located and are of sufficient length to give the athlete adequate control during voluntary directional changes, especially on down grades.

CONCLUSION

The problem of directional instability of racing wheelchairs can adequately be solved by using the crown compensator mechanisms discussed in this paper. However, several problems deserve further investigation, in order that more disabled people can safely enjoy the benefits of the physical exercise made possible through wheelchair racing. One area of particular importance seems to be that of determining the optimal position of the body with respect to the racing wheelchair.

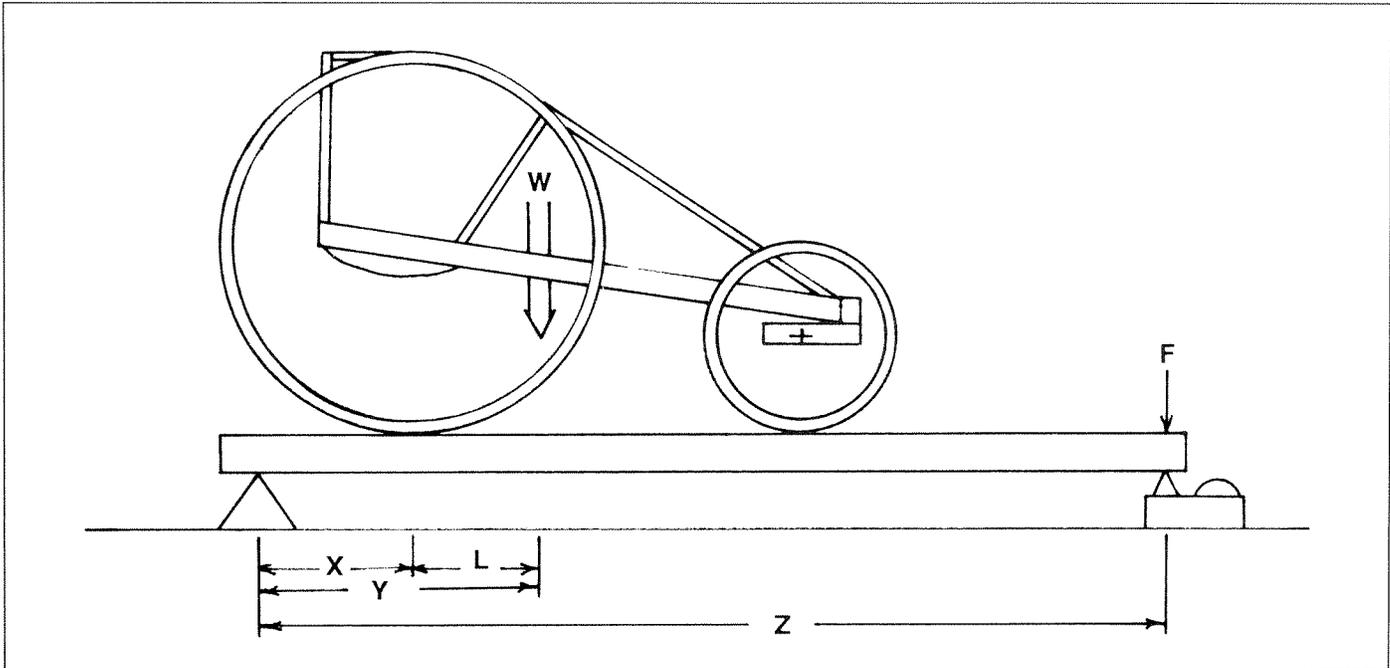


Figure 7.
Center of gravity measurement.

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