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Wheelchair prescription: an analysis of factors that affect mobility and performance*

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INTRODUCTION

A reasonable expectation for both the potential user and prescriber is the selection of a wheelchair that allows maximum performance and mobility for the user. Similarly, it would seem to be in the interest of providers, vendors, and manufacturers to deliver a wheelchair compatible with maximum performance and mobility. While it is difficult to obtain hard information on the efficacy of wheelchair prescription, anecdotal evidence seems to indicate that it is less than optimal and quite variable, particularly in the case of the first prescription for a prospective user. Even if most of the anecdotes on poor wheelchair prescriptions are apocryphal — which they likely are — there is little margin for doubt that wheelchair prescription could not be much better than it is.

The problem is related to the larger issue of service delivery. The time and expense necessary to gain acceptance for a new product has had a restrictive effect on research and development and technology transfer, nearly to the extent of suppression. The inertia of the service delivery system has had the predictable effect of perpetuating what might appropriately be called the 'generic' wheelchair. This wheelchair has the following characteristic features: tubular construction, sling seat and back suspended from horizontal and vertical frame members (respectively), X-brace folding mechanism, front casters (usually 8 inches), and rear drive wheels with hand rims (usually 24 inches and 22 inches, respectively) mounted on the rear vertical frame member. It is this last characteristic feature along with the fixed seat position that is the principal determinant (or perhaps, more accurately, deterrent) of performance potential. Nearly every major manufacturer of wheelchairs has this generic model as its basic product. The generic wheelchair is the most often prescribed wheelchair in the world today by a wide margin. It is easy enough to hypothesize that this design resulted from a motivation for simplicity and economy of construction. That was fifty years ago. It is much more difficult to justify its continued pre-eminence in the marketplace.

If a group can be singled out for responsibility of improvement in wheelchair technology it is the athletes who have adapted them to their needs. They have demonstrated what wheelchairs can be. Lightweight wheelchairs used for sports have been commercially available for a relatively short time. The unfortunate designation of 'sports chairs' has hindered the wider acceptance of these wheelchairs. This is largely due to the myopic view of third-party payers and others who have made them difficult to obtain (and still do).

In the past decade wheelchair racing athletes have set new records for the mile (1/4 mile track) — from approximately 6 minutes to less than 4 minutes — and for the Marathon from 3 hours to 1 hour and 40 minutes. Athletes maneuver through complex slalom courses, climb curbs 11 inches high, and play basketball and racket sports with remarkable skill. These accomplishments are due in large part to the physical skill and commitment to training on the part of the athletes, but no

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knowledgeable person would suggest or believe that these feats could be performed with a generic wheelchair.

After ten years of observation, thought, study, and research on wheelchairs and wheelchair performance, I have reached the conclusion that the process of prescribing and providing wheelchairs is inverted. Rather than prescribing and providing generic wheelchairs as a general practice and requiring justification for an extended use (sports) wheelchair, it should be exactly opposite. A prescriber should be required to provide justification to prescribe a generic wheelchair. This will likely be considered heresy by some (perhaps, many) wheelchair prescribers and providers and even some users. Hopefully the following analysis will provide additional support for my position.

ANALYSIS OF FACTORS AFFECTING PERFORMANCE

A primary determinant of performance for propulsion, control, and maneuverability of manual wheelchairs is the distribution of mass with respect to the axis of the main wheels. Mass distribution is determined primarily by the vertical and horizontal position of the seat relative to the axle, and to a lesser extent by the inclination of the seat and backrest and the position of the footrests. The performance factors that are significantly affected by user position relative to the main axle position include rolling resistance, propulsion efficiency, downhill turning tendency, turning and maneuverability, static and dynamic stability, and barrier negotiation.

The purpose of this paper is to present an analysis of the effect of user position with respect to these various performance factors as a basis for optimization of performance.

Rolling Resistance

The optimization of rolling resistance (R.R.) with respect to mass distribution is independent from user characteristics. Rolling resistance is primarily a function of wheel (and caster) characteristics, laden weight, and weight distribution. Nearly all manufacturers appear to be sensitive to the first two of these factors, as is evident from the marketing of "lightweight" wheelchairs and the provision for wheel and caster options. The significance of mass distribution is apparently less widely appreciated. The rolling resistance of a wheel decreases as an inverse function of its diameter, which means that with other factors constant the rolling resistance of a large wheel is less than that of a small wheel. If the center of mass is located nearer the drive wheels (and farther from the casters) the wheelchairs will have a lower rolling resistance and, therefore, will require less energy to propel. Rolling resistance is due to hysteresis of the tire material and varies according to the modulus of the material (3). Data are provided in **Figure 1** for rolling resistance of 24 inch wheels with solid gray rubber tires and for 60 percent weight distribution on the 24 inch wheels and 40 percent on 8 inch casters of the same material at different laden weights. Some sample calculations will demonstrate the effect of moving the center of mass nearer the main axle:

Wheelbase = 16″; Weight Distribution: 60% main wheels and 40% casters (c.g. is 6.4″ forward of main axle); R.R. at 850N laden wt. = 12.1N for 24″ wheels only and = 14.2N for wheels and casters **(Figure 1)**

(R.R. is the retarding force acting in the line of progression. Laden weight is the vertical loading.)

If R.R. for wheels only is set to unity the R.R. for wheels and casters will be:

$$14.2 \div 12.1 = 1.17$$

The ratio of R.R. of caster to wheels can now be determined by the equation:

% wheel weight × 1.0 + % caster weight × R.R. ratio = 1.17, i.e., R.R. ratio = 1.43

For a 75% wheels, 25% casters distribution (c.g. 4″ from main axle) the relative R.R. is:

$$(.75 \times 1) + (.25 \times 1.43) = 1.10$$

The reduction in R.R. by moving the c.g. 2.4″ rearward is, therefore:

$$(1.17 - 1.10) \div 1.17 \sim 6\%$$

While this may appear to be a small reduction, it may be significant for the marginal user and probably for any user over prolonged activity. It should be noted that the data in **Figure 1** were obtained from a treadmill. Rolling resistances are typically 1.5 times greater on concrete and 5 times greater on deep pile carpets. These surfaces affect the rolling resistance of caster more adversely than the drive wheels, which would result in greater relative reduction in rolling resistance by positioning the center of gravity nearer the main axle. Those unimpressed by a 6 percent reduction in rolling resistance might consider being at the finish line of a marathon without running the last 1.6 miles.

Propulsion Efficiency

Wheelchair propulsion efficiency (PE) has been found to be affected by many variables. These include user dimensions and capacities, user position, method of propulsion, wheelchair characteristics, and mechanical advantage. The factor of most practical significance for rim-propelled wheelchairs is user position relative to the drive wheels.

The efficiency of wheelchair propulsion, as in any other repetitive physical task, is dependent upon the conditions of muscle contraction, including frequency, duration, force and velocity of contraction, and relative muscle length. Muscle contraction approaches maximum efficiency when contracting at a frequency of 50 to 60 cycles per minute and at tension and shortening velocities of approximately 30 percent of their respective maximum values. The typical fixed mechanical advantage of most general use wheelchairs is inconsistent with these values for most active users and is the main limiting factor of propulsion efficiency. While this imposes an upper limit on efficiency it is still possible to make significant improvements.

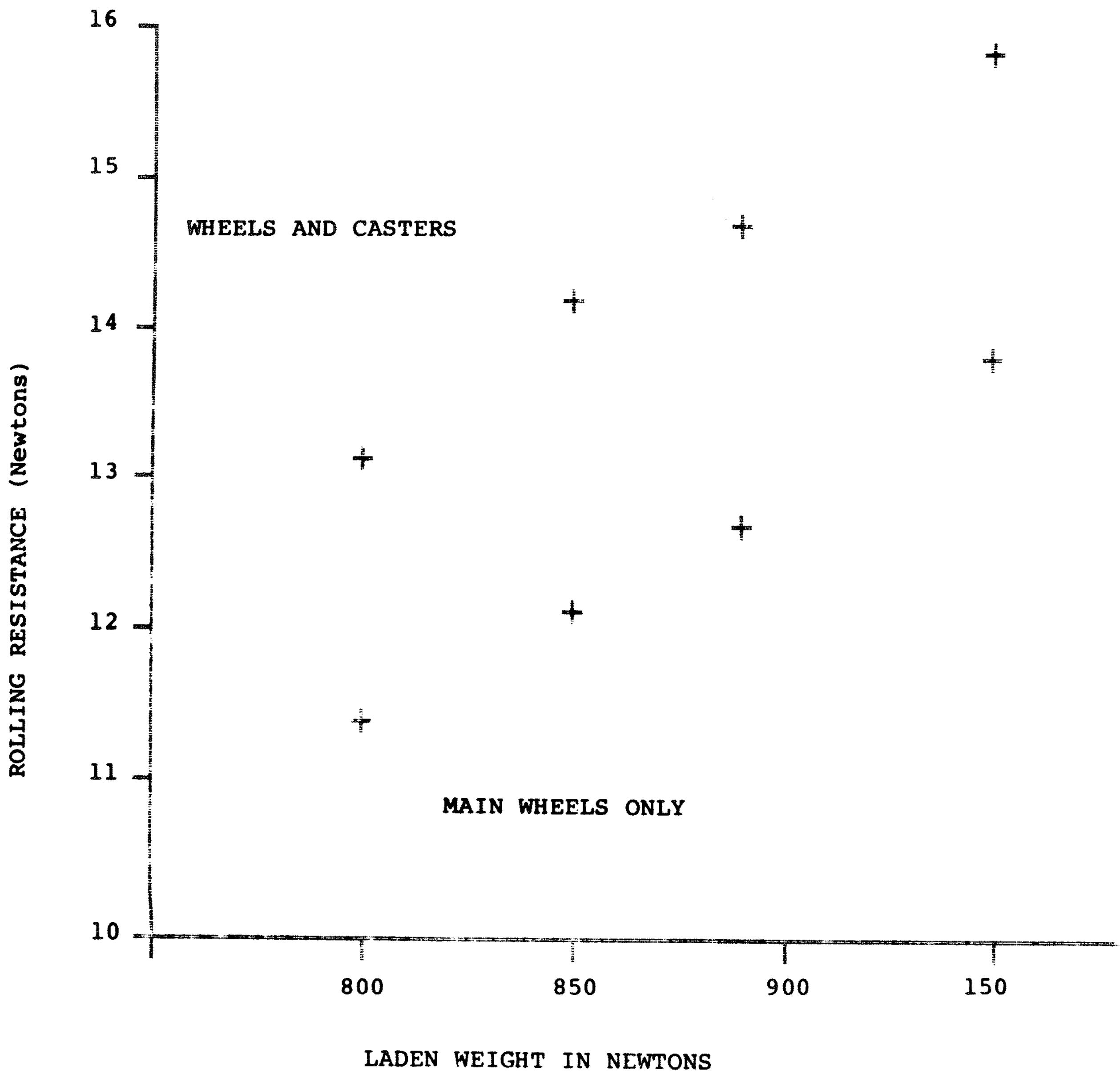

Figure 1.
Effect of mass distribution of wheelchairs on rolling resistance.

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The principal determinant of muscle function, and, therefore, efficiency, for general use rim-propelled wheelchairs is upper limb-segment geometry during the propulsion cycle, which is secondary to user position relative to the push-rims. Principal considerations in optimization of PE are horizontal and vertical positioning to maximize the effect of gravity and minimize muscle activity during the recovery portion of the propulsion cycle. Recent evidence suggests the latter to be the most important factor in the determination of PE (1,2). Energy cost measurements obtained under conditions of unilateral propulsion revealed higher efficiency than with bilateral propulsion. The most reasonable explanation of this phenomenon is the more suitable conditions with respect to the force-velocity conditions of the muscles and the reduction of recovery strokes by approximately half.

In addition to the conclusive empirical evidence of the superiority of a more rearward seat position relative to the drive wheels, the advantage of this positioning in terms of propulsion efficiency has been verified independently by at least a dozen different investigators. There has been less investigation with respect to vertical positioning. However, a recent electromyographic analysis has revealed that optimization of the propulsion stroke with respect to efficiency is consistent with minimization of EMG activity during the recovery phase of the cycle (1). This position is a function of upper extremity length and the location of the shoulder joint axis relative to the wheel position. We anticipate that it will be possible to develop a predictive algorithm for the determination of optimal position based on these variables.

Side Slope Effect

The nearly ubiquitous side slope of improved outdoor surfaces produces a downhill turning tendency (DTT). This DTT is approximately proportional to the normal horizontal distance from the center of mass to the drive wheel axis. The energy cost of propelling a typical wheelchair on a 2-degree side slope has been found to be about two times that required on a level surface(3). While other factors such as wheel width, wheel base, camber, and caster trail affect DTT, minimization of DTT is most effectively and practically achieved by moving the center of mass toward the main wheel axis.

Pitch Axis Control

Static stability (SS) about the pitch axis increases in proportion to the normal horizontal distance from the axis to the center of mass. Based on the number of generic wheelchairs manufactured and prescribed, SS would appear to be desirable. The ability to control the attitude of a wheelchair about the pitch axis is, in fact, inversely related to SS. It can be shown that the manipulation of a wheelchair in the 'wheelie' position, which is necessary to maximum maneuverability and curb-climbing, is enhanced by increasing the vertical and decreasing the horizontal normal distances from the center of mass to the wheel axis. It also can be shown that manipulation of the wheelchair about the yaw axis is improved by decreasing the normal horizontal distance from the center of gravity to the axle. The degree of control of the wheelchair about the pitch axis that can be exerted by the user with spinal cord injury is greatly influenced by the level of disability. Manipulation of the user's trunk segment and the location of the center of mass appear to be the factors most important to control about the pitch axis.

Diagrams to help explain mechanisms of pitch axis control are presented in **Figure 2. Figure 2a** is a representation of the approximate mass distribution of a paraplegic in a generic wheelchair. Locations of approxi-

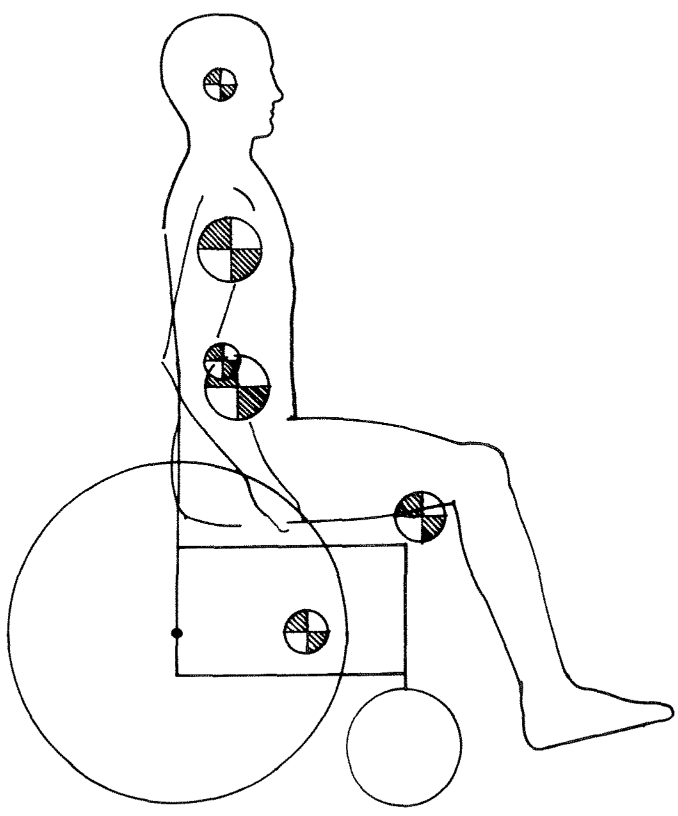


Figure 2a.
Estimated mass distribution for a paraplegic in a generic wheelchair.

mately proportional segment masses are shown for the head, upper trunk, lower trunk, upper extremity, lower extremity, and wheelchair frame. These masses have been combined into two discrete mass locations consisting of lower trunk, lower extremity, and wheelchair frame, which are assumed to move about the main wheel axis in a constant position with the frame at a fixed radius. The head, upper trunk, and upper extremities, which are free to move as a unit mass with respect to the wheelchair, thereby alter the mass distribution relative to the wheelchair. **Figures 2c and 2d** provide a comparison of mass distribution between the generic wheelchair position and the center of mass moved rearward 2.4 inches. **Figures 2e and 2f** show the relative angular displacements necessary about the pitch axis for the generic wheelchair and adjusted center of gravity wheelchair to achieve a balanced 'wheelie' position, respectively, when the component masses are maintained relative to the wheelchair frame. **Figure 2g** illustrates the necessary rearward displacement of the movable mass to place the center of gravity of the system over the axle, and **Figure 2h** illustrates how movement of this upper mass relative to

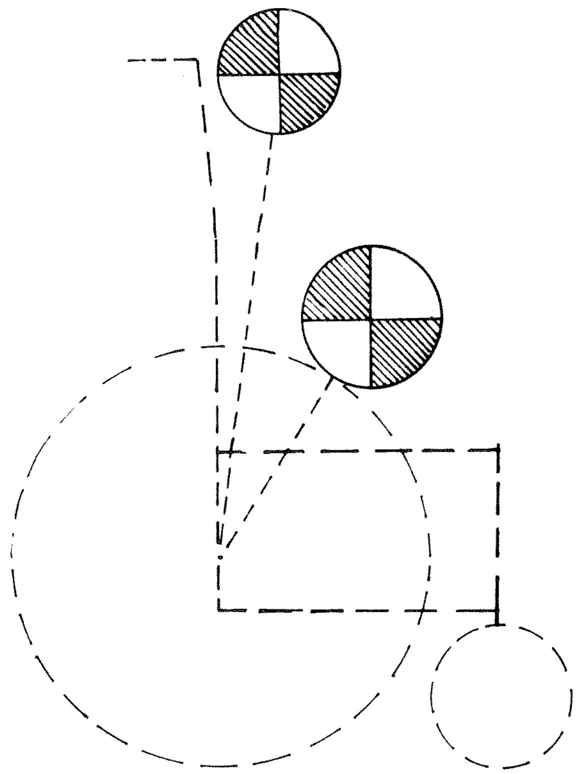


Figure 2c.
Mass distribution for a generic wheelchair.

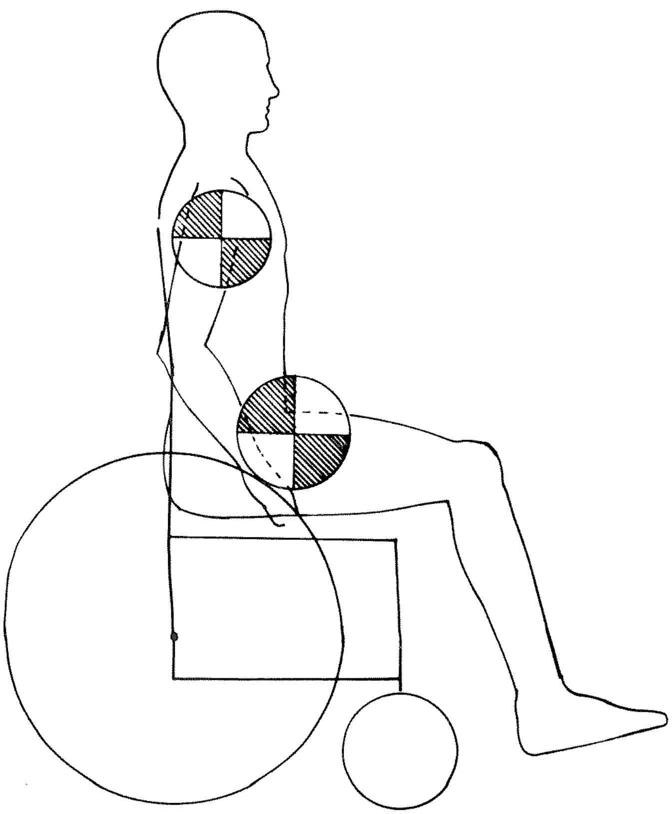


Figure 2b.
Location of fixed and movable mass components (generic wheelchair).

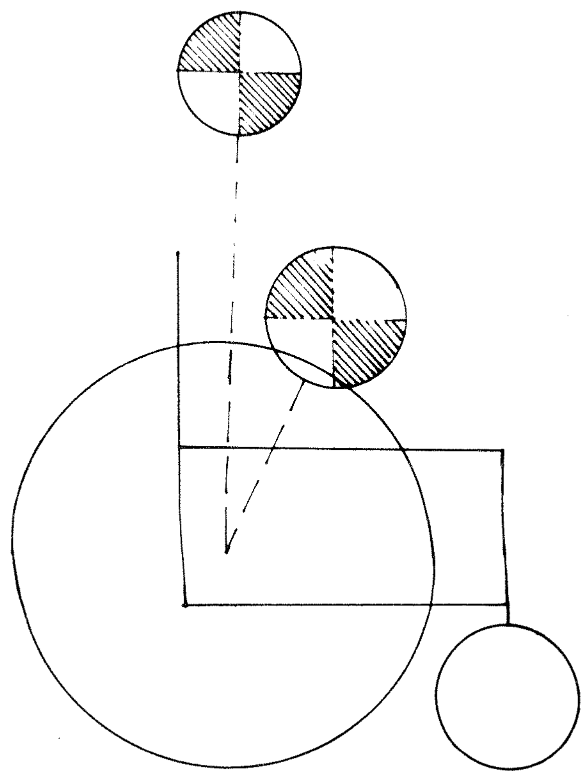


Figure 2d.
Mass distribution for 75 percent 25 percent loaded wheelchair.

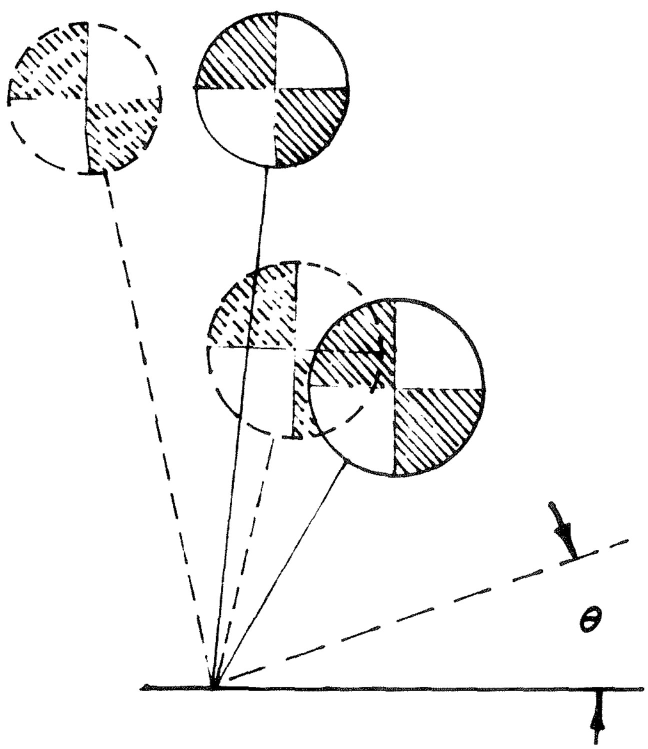


Figure 2e.
Relative angular displacement to wheelie position for generic wheelchair.

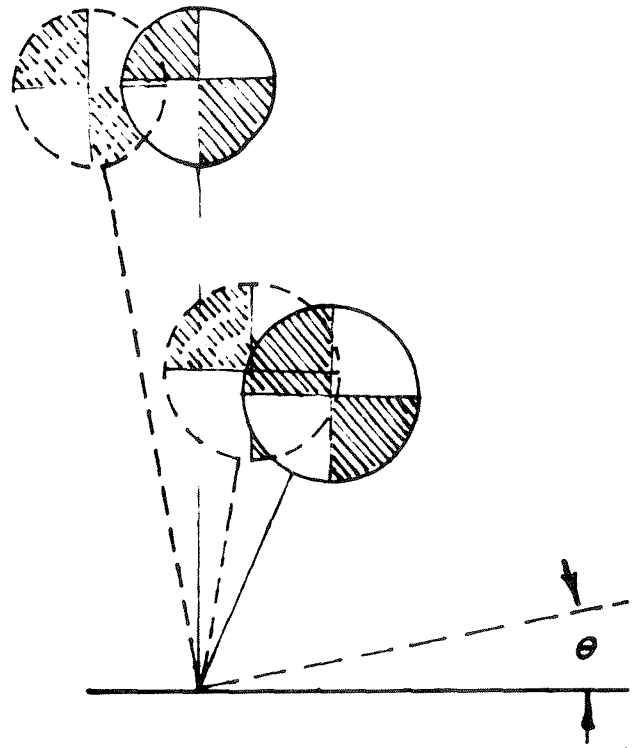


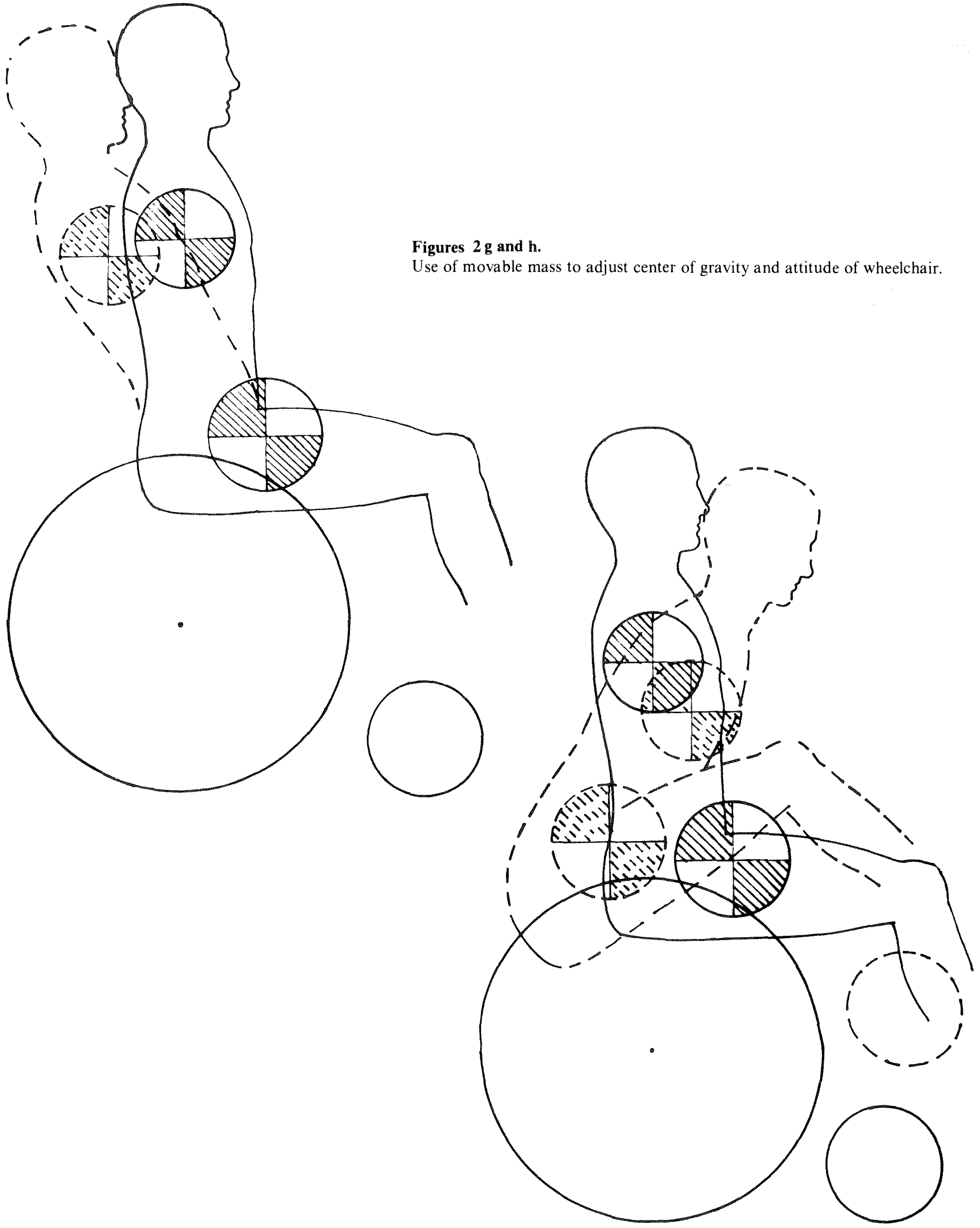
Figure 2f.
Relative angular displacement for 75 percent/25 percent wheelchair.

the fixed mass provides control about the pitch axis.

There are three possible mechanisms to produce angular displacement of the wheelchair about the pitch axis: generation of an angular impulse via the handrims to 'drive' the wheelchair under the center of gravity **(Figures 2e and 2f)**; displacement of the movable mass segment behind the axle so that the wheelchair will react to gravity **(Figure 2g)**; and, a combination of both. Observation of videotaped performances of the 'wheelie' maneuver executed in curb climbing, rapid deceleration at high speed, and in balancing reveal the control mechanism to be a function of both force application to the handrims and body control with the latter being the obvious factor in initiating the 'wheelie.' It is also evident from both observation and **Figure 2** that a more rearward placement of the center of gravity provides for better control. The extent of trunk motion is significantly affected by the seat back height. Due to the importance of this motion to control of the wheelchair the seat back should be as low and otherwise non-restricting as is compatible with the individual user's requirements for support. Contemporary prescription practice is quite conservative in this respect.

SUMMARY

Clearly, all considerations for wheelchair performance and their applicability to optimization of mobility are related to user position relative to the main wheel axis. It is also obvious that wheelchair performance is enhanced by a center of gravity position rearward of that which is characteristic of the generic wheelchair. The only obvious features of the generic wheelchair are excessive static stability and limitation of body motion. Perhaps at this stage the reader may be ready to accept some of the arguments presented above, but have reservations about prescribing a less stable wheelchair for the more severely disabled (e.g., quadraplegics). Consider that the reduction of rolling resistance, decrease in downhill turning tendancy, and required turning force would likely be even more important to the user with marginal physical capacity. This would appear as an attractive trade for reduction in static stability. The number of factors unfavorably affected by increased static stability would suggest the use of an anti-tipping device rather than designed static stability if this is thought to be an important consideration.



Figures 2 g and h.
Use of movable mass to adjust center of gravity and attitude of wheelchair.

I would like to restate with emphasis the conviction that a 'generic' wheelchair should never be prescribed for anyone who is expected to manually propel the wheelchair without explicit justification. If the first-time user is provided with a wheelchair that has horizontal and vertical seat (or wheel) adjustment it is unlikely that he/she will want to discard it after a few months when skill, knowledge, and mental outlook have improved.

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