Technical Considerations

Ergonometric Considerations

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INTRODUCTION

Wheelchair performance is directly related to the client's position in the wheelchair. Client position, i.e., the distribution of mass with respect to the wheel axis and the position of the client's shoulder axis relative to the handrim, is related to several ergonometric factors:

Rolling Resistance (RR)
Downhill Turning Tendency (DTT)
Yaw Axis Control (YAC)
Pitch Axis Control (PAC)
Propulsion Efficiency (PE)
Static Stability (SS)
Weight/Portability

These factors influence performance as follows:

Rolling Resistance (RR): The conventional configuration results in a weight distribution with approximately 60 percent on the main wheels and 40 percent on the casters. By moving the seat rearward 2.5 inches, the weight is redistributed to a 75 percent/25 percent ratio. If other factors remain constant, this has been found to reduce RR by 6 percent (1) **(Figure 1)**. While this difference appears small, it could be quite significant over a long distance for a marginal wheelchair user.

Downhill Turning Tendency (DTT) or **Side-Slope Effect:** Whenever there is a lateral incline there is a DTT. Since virtually all improved outdoor surfaces have a 1- to 2-degree slope for drainage, this is an ever-present condition. A 2-degree slope results in nearly a two-fold increase in the energy required to propel a conventional wheelchair (2). Moving the seat rearward shifts the center of gravity and significantly reduces DDT (**Figure 2**. See also **Figure 4b**).

Yaw Axis Control (YAC): The forces required to maneuver the wheelchair are inversely related to the polar moment of inertia of the wheelchair. This moment of inertia can be reduced by decreasing the distance from the main axis to the center of gravity by moving the seat rearward.

Pitch Axis Control (PAC): The ability to do a wheelie is essential for curb-climbing and provides for a greater degree of control and maneuverability (**Figure 3**). Pitch axis control is inversely proportional to the moment of inertia (1) and is improved by a rearward seat position. The trunk also has a large moment of inertia and is important in pitch axis control. A high seatback can limit the range of motion of the trunk and therefore limit the effect of trunk motion in PAC.

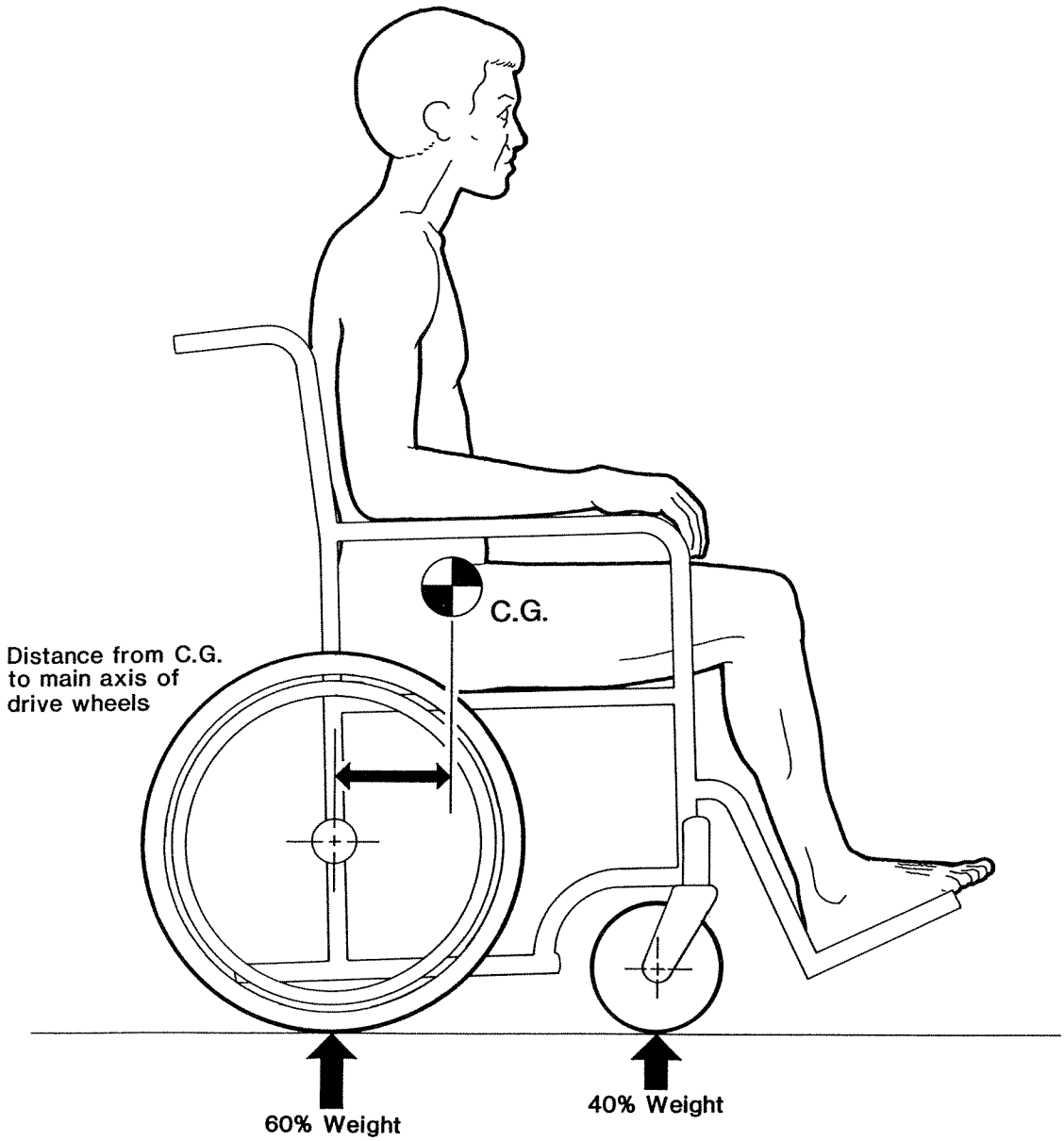


Figure 1.
One of the most important factors affecting wheelchair performance is the distribution of mass on the wheels. The horizontal distance between the center of gravity (c.g.) of the combined mass of wheelchair and occupant (represented by the circular target) and the axle of the main drive wheel determines the distribution of mass between the rear and front (caster) wheels.

Propulsion Efficiency (PE): Propulsion efficiency is related to the above factors and is also consistent with a more rearward seat position (3,4). Optimizing PE requires minimizing energy consumption in the recovery phase of the propulsion cycle (5). This depends on both the fore-aft and the vertical position of the seat. The conventional position requires excessive internal rotation, extension, and shoulder elevation in the recovery phase, in order to grab the rim for the stroke. If the client is ideally

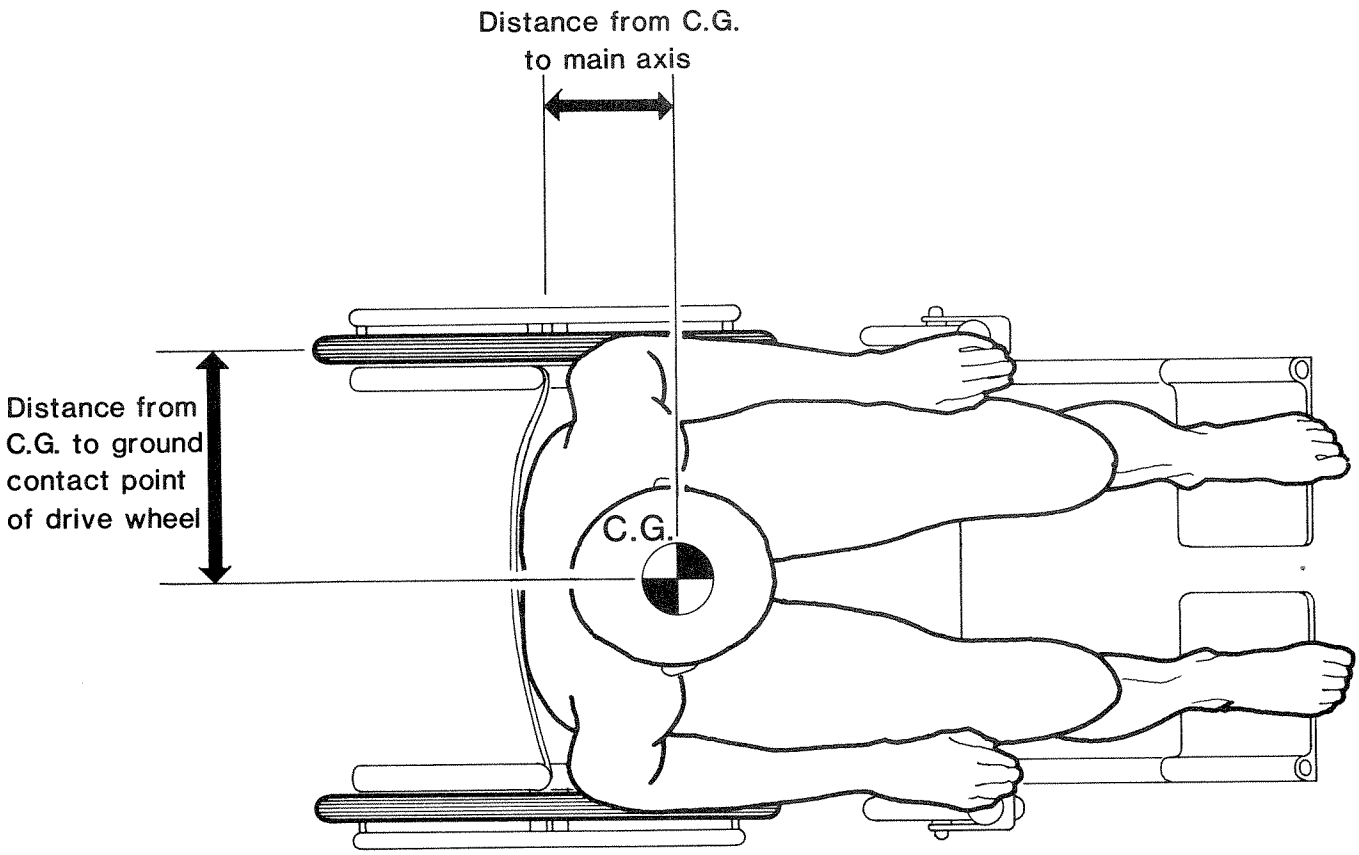
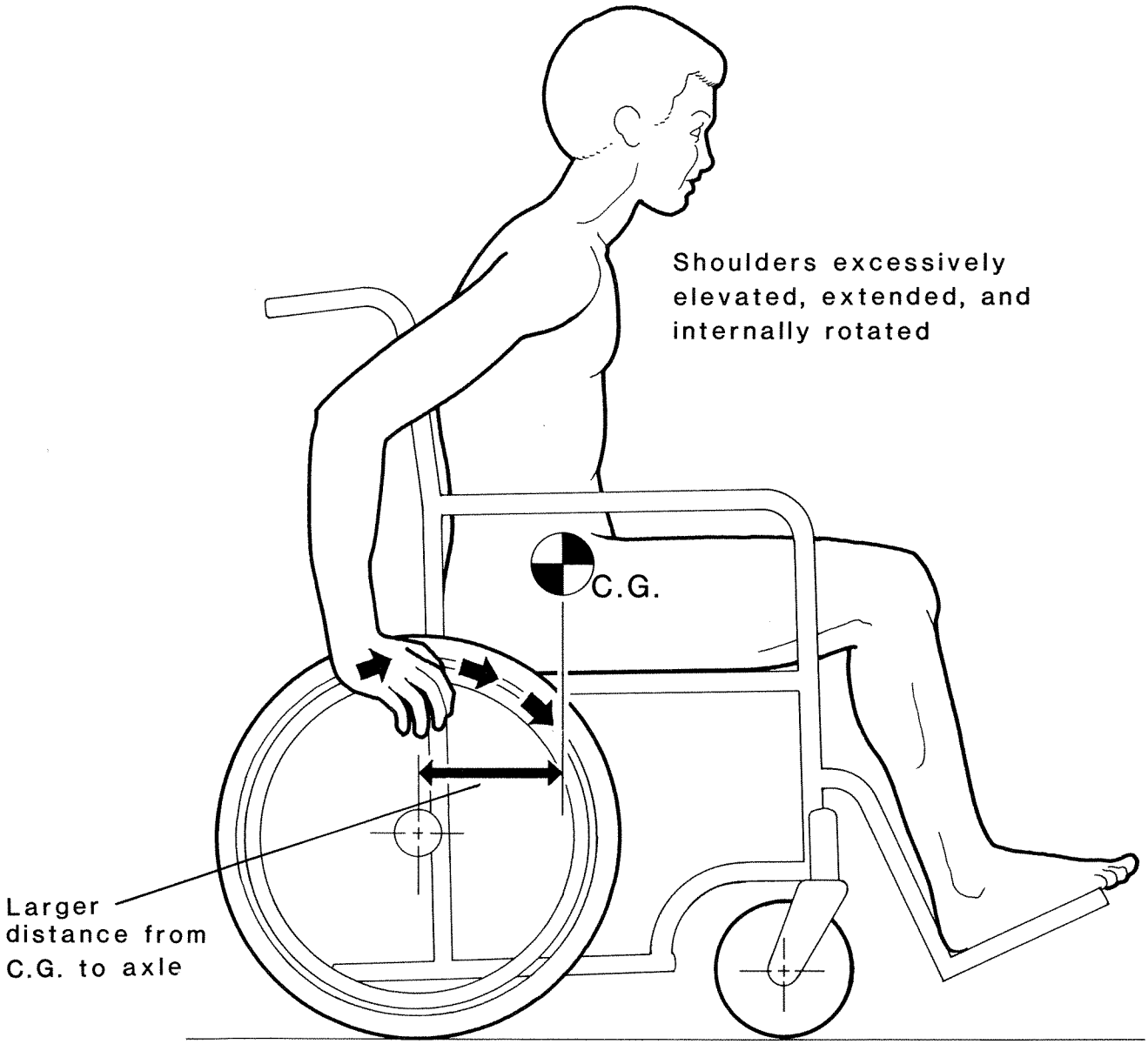


Figure 2.
The tendency toward turning downhill (DTT) and the ease of, or resistance to, turning while moving (YAC) are both related to the horizontal distances between the c.g. of the system mass and the axle or ground contact point of the drive wheels. The magnitude of the combined mass and the distances are elements of the polar moment of inertia of the system.

Figure 3.
Wheelie balance. The ability to balance a wheelchair on its rear wheels is essential for curb climbing, as well as for providing extra control and maneuverability.



Figures 4a and 4b.
Figure 4a: If the user is too far forward or too low, the shoulders are excessively elevated, extended, and internally rotated and the propulsion stroke is predominantly downward.

positioned, i.e., rearward, the recovery phase is initiated by gravity and requires little or no muscular effort (**Figures 4a** and **4b**).

Static Stability (SS): While it is evident that the SS of the wheelchair is reduced with rearward seat placement it is doubtful if the consequence is well understood. The increased PAC and the lesser angular displacement required to reach the balance point make it much easier to recover from an

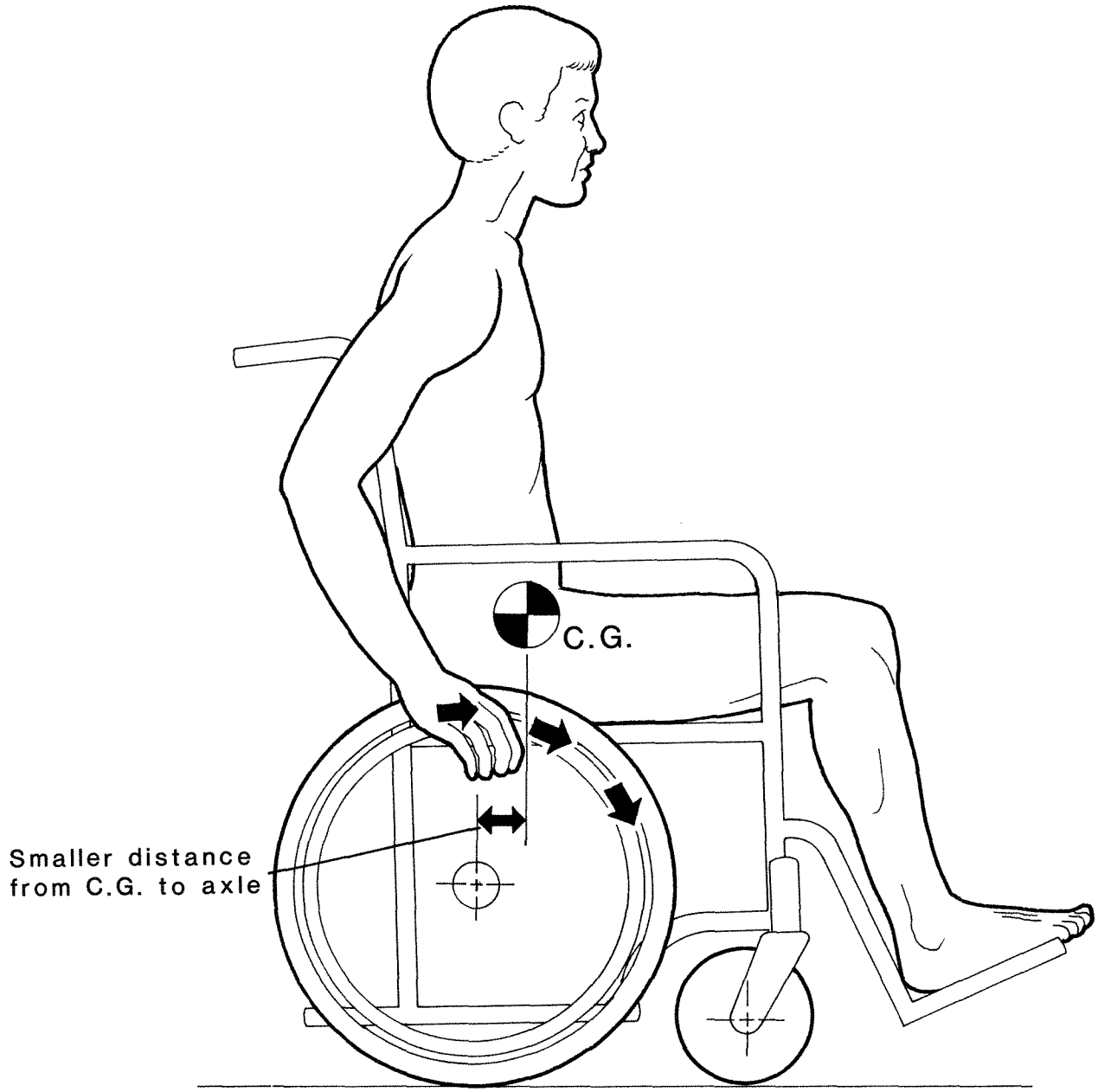


Figure 4b: If the user is higher or horizontally nearer the wheel axis, shoulder position is more normal and the propulsion stroke is more horizontal.

unstable position. The importance of SS is probably over-estimated by most prescribers.

Weight/Portability: Weight/Portability has very little effect on the propulsion performance of a wheelchair on level surfaces. The additional cost associated with lightweight chairs is justified only if the client often needs to propel the wheelchair on grades, or if the wheelchair is loaded and unloaded frequently from a vehicle by hand.

MEASUREMENT: FITTING A PERSON TO THE MANUAL WHEELCHAIR

Unless there is a specific need for postural support (e.g., correction or prevention of deformity) the measurement process should be consistent for most clients. It is best accomplished if one or more sample wheelchairs are available. Both the accuracy and ease of measurement are facilitated with proper instruments. An anthropometer is desirable, although the task can be accomplished with a tape measure and a ruler.

In every case the selection of a seat cushion must be made prior to measuring for the wheelchair. Dimensions should be measured with the client seated on the cushion that will be used with the wheelchair. The most critical dimensions for seating are seat width, seat depth, and seatback height. (See also: Seat Cushion Selection, by Martin W. Ferguson-Pell, pp. 49-73.)

Seat Width: If the wheelchair has a sling seat (this will usually be the case) the seat surface will be somewhat concave. The degree of concavity is affected by the cushion. The distance between the sling supports (seat frame tubes) should be equal to the client's bi-trochanteric diameter (**Figure 5**). This measurement should be taken by compressing the arms of the anthropometer against the greater trochanters and interpreted with respect to the manufacturer's seat width dimension. However, with an obese client, the width should be the minimum distance that avoids lateral compression of soft tissue by hard points on the wheelchair. The consequence of a narrower seat width is the possibility of pressure concentration on the client from the seat frame or armrest panels (if present). A wider seat can result in instability and an overall wider wheelchair with the obvious consequence of reduced accessibility (e.g., narrow doorways).

Seat Depth: The seat surface is the principal weight-bearing structure and supports the weight of the trunk and thigh segments. To minimize pressure (i.e., the weight/surface ratio) the thigh segment should be supported over most of its length. When the client is properly seated against the seatback, the front edge of the seat surface should be no more than 2 inches from the popliteal crease with his/her back, including the lumbar surface, firmly in contact with the seatback (**Figure 6**).

Seat Angle: The seat should be inclined from 1 to 4 degrees above horizontal (**Figure 7**). This will pro-

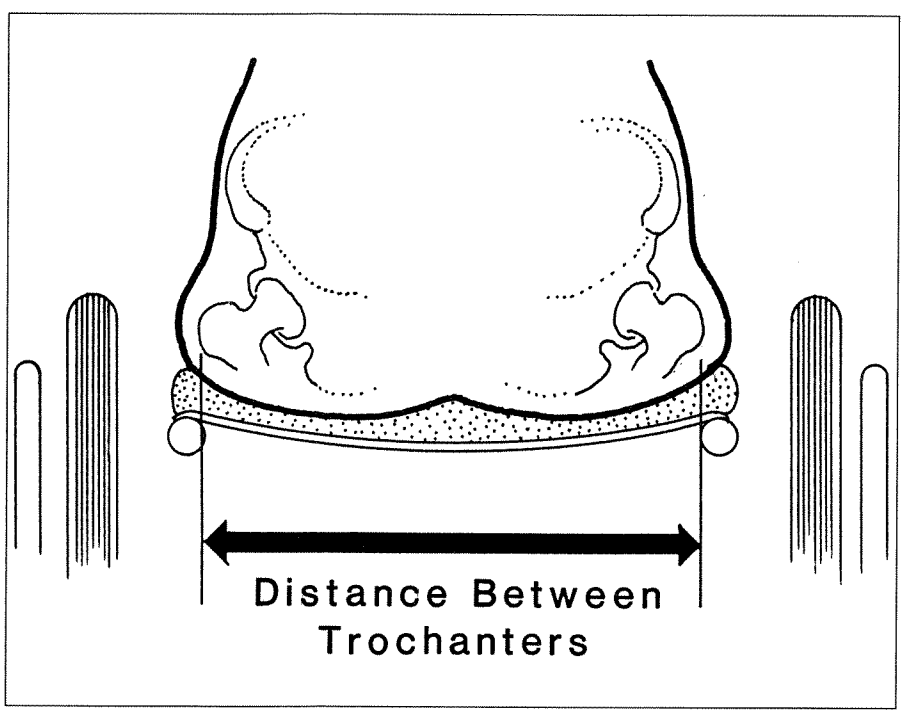


Figure 5.
The width of the seat is very important for posture, propulsion efficiency, and pressure distribution. The distance between the seat rails should be equal to the distance between the user's trochanters.

vide a small rearward force which will help keep the client positioned in the chair. A larger angle could put a strain on the hip extensor muscles (hamstrings) precipitating spasms (and perhaps other undesirable effects) unless the knees were flexed a comparable amount. This would impact on other dimensions such as legrest/footrest position and require an unconventional (and probably incompatible) geometry for most wheelchairs.*

Seat Height: Seat height, legrest angle and length, and vertical positioning are interdependent. Seat height is also limited by environmental factors such as furniture dimensions. An environmentally compatible floor-to-seat distance (i.e., 17 to 21 inches) contributes to optimal performance (**Figure 7**). In addition, a sufficient seat-to-shoulder vertical distance allows a propulsion-recovery motion (i.e., from rim release to grab position) that does not require excessive shoulder elevation. An unusually tall, short, or atypically proportioned client (e.g., long torso with short extremities or vice-versa) may pose a challenge in determining seat height. In extreme cases it may be advisable to consider non-standard main wheel and/or handrim diameters. One must also consider that the seat cushion typically adds 2 or more inches to the seat height.

Within these limitations, the primary determinant of seat height should be the shoulder-to-wheel vertical orientation. The seat will be very close to optimum height if the elbow flexion angle is approximately 120 degrees when the handrim is grasped at the highest point (**Figure 7**). Optimization can be achieved by having the client propel the wheelchair at this seat height at 1 inch above and 1 inch below this height. The clinician must observe the elbow angle from a point normal (perpendicular) to the plane of the arm and forearm, because if the client is observed directly from the side, the elbow angle will appear more acute due to the perspective created by internal rotation at the shoulder joint. If this position cannot be attained, then compromises must be made either in rim/wheel diameters or legrest length/angle dimensions.

**Editor's Note.* Also, too much of a seat angle (knees higher than buttocks) can increase ischial/sacral pressure causing tissue compromise.

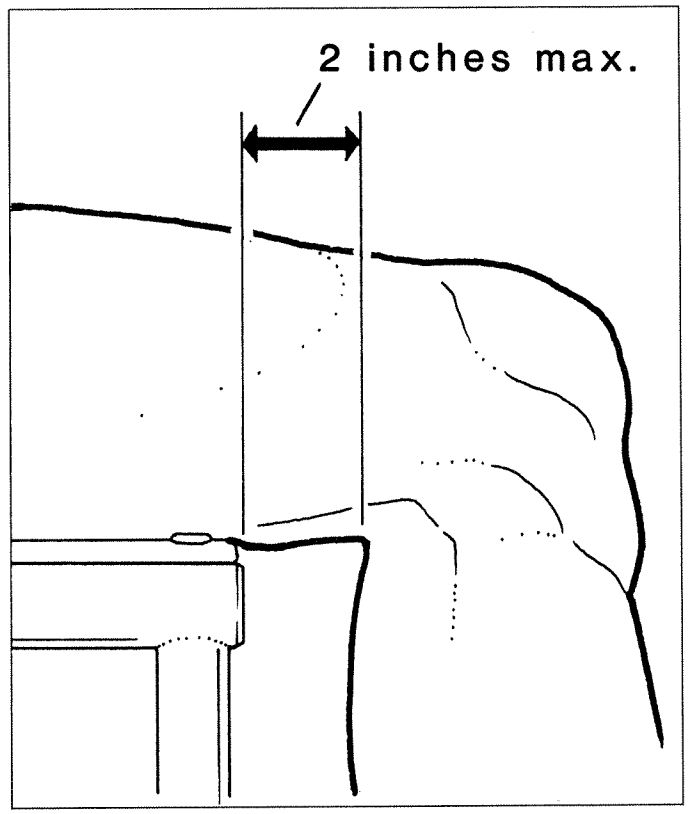


Figure 6.
To assure that the weight is distributed over most of the length of the thigh, the space between the front edge of the seat upholstery and the popliteal crease behind the knee should not exceed 2 inches.

Horizontal (fore-aft) Positioning: Propulsion efficiency is significantly affected by the orientation of the client to the drive wheels. In the standard wheelchair configuration the shoulder axis is approximately 1 to 2 inches in front of the wheel axis. However, for efficient propulsion it should be about 2 inches or more behind the wheel axis. The best position will be determined by trial and error, therefore the client's position of choice is likely to change with experience, as will any apprehension related to decreased stability. For the typical client, the seat post should be from 1/4 to 1/3 of the trunk depth (fore-aft sagittal trunk dimension) forward of the client's dorsal surface (**Figure 8**). The optimum position will vary slightly based on the degree of disability (e.g., double amputee versus SCI, and quadriplegic versus paraplegic).

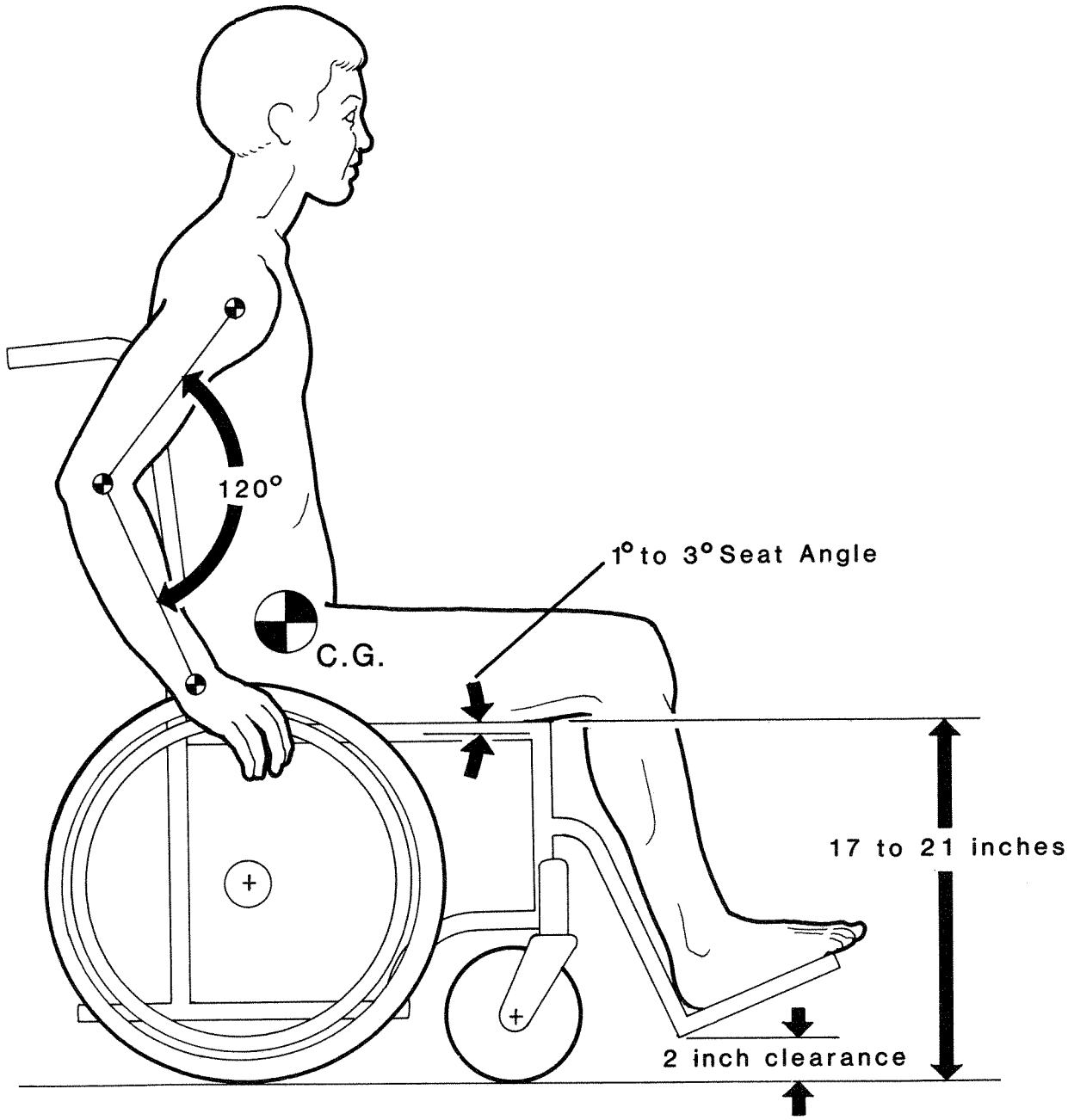


Figure 7.
Seat height and angle have an important influence on posture and propulsion efficiency. The seat will be very close to the optimum height if three criteria are satisfied: 1) the elbow is flexed at approximately 120 degrees when the handrim is grasped at the highest point; 2) the seat angle is between 1 and 3 degrees; and, 3) the footrests clear the ground by 2 inches. All measurements should be made with the cushion in place. Under these conditions, the most common resulting heights at the front of the seat are between 17 and 21 inches.

Back Height: The backrest affects two important functions—trunk support and trunk mobility. The trunk has the largest moment of inertia about the pitch axis of the wheelchair and is therefore the most important body segment to PAC. The importance of PAC to the client must be balanced with his/her need for trunk support. The functional level of the client should be the major consideration when determining the appropriate seatback height. While it is not likely to be discussed in terms of PAC and

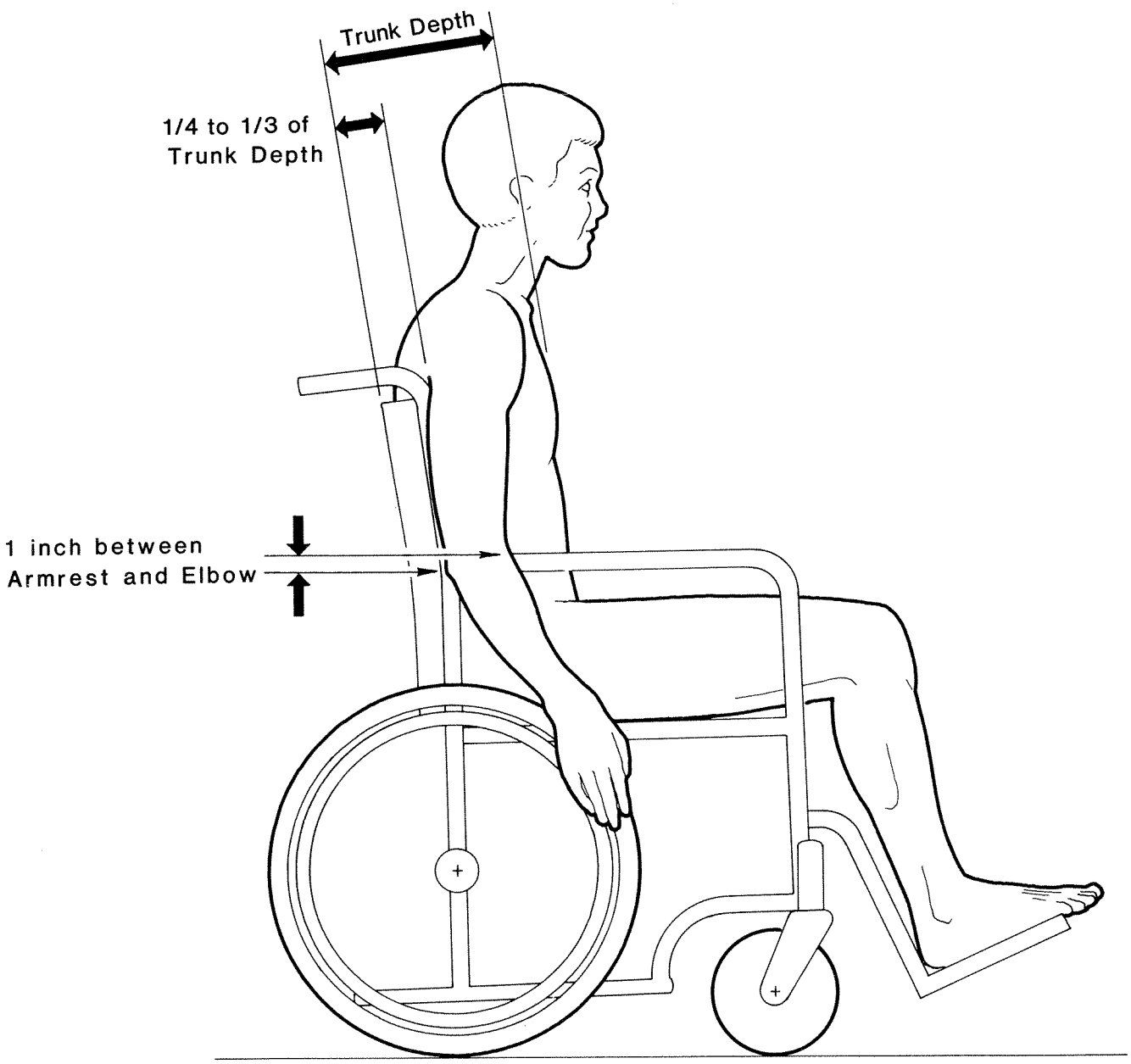


Figure 8.
The metal tubes of the arms and back of the chair can be used as guideposts for measuring optimum fore and aft positioning. The back posts should be one-quarter to one-third of the thickness of the trunk forward of the dorsal surface of the trunk. The top surface of the armrest should be 1 inch higher than the olecranon process of the elbow when the user's arms are pendant and relaxed.

moment of inertia, the popularity of the low seat back is apparent from the numbers of sports chairs with low seatbacks in use. Apparently, there has been no investigation of the potential for spinal deformity with long-term use of low seat backs despite concerns often expressed by clinicians. As this remains a moot issue for the present, most clinicians are likely to be more comfortable with a conservative approach.

Unrestricted shoulder girdle mobility is essential if the client is expected to propel the wheelchair. This requires that the top edge of the seatback be no higher than the inferior angle of the scapula. A seatback height below the scapula should not be

prescribed for clients without good trunk control (i.e., at least mid-thoracic or lower). In order to provide additional spinal support, a seatback higher than the inferior angle of the scapula can still allow relatively unrestricted shoulder motion if the upper corners are sufficiently rounded or cut out. This condition can be achieved with a solid-back seat which is seldom available except as a custom feature.

Back Width: The seatback width should be compatible with the conditions noted above for shoulder mobility. This dimension should be narrow, consistent with the client's maximum trunk width plus an additional lateral clearance of 1/2 inch between the client's trunk and the seat post. This measurement will usually be taken at the top of the seatback.

Unfortunately, for most wheelchairs seatback width is not a variable, but is determined by the seat-width specification. A probable consequence is a compromise between seat width and back height to attain the desired shoulder mobility. This could be a problem if there is disproportionality between hip width and shoulder width. This situation is most likely to occur with female clients.

An additional consideration is the concavity of the seatback. Since most wheelchairs have a sling back this will be a function of the width of the seatback fabric. Lateral trunk support can be obtained by the "wraparound" effect, but it should be noted that this can affect the seat depth.

Back Angle: This angle, not critical for most clients, is usually fixed. The seat post is perpendicular to the horizontal seat frame, and the apparent angle is a function of the laxity and uniformity of the width of the seat-back fabric. The client's trunk range is usually 2 to 5 degrees behind vertical in a sling back. The only adjustment, other than a reclining back, is in the tension of the seatback fabric. However if a non-standard back angle is required, a cushion insert such as a lumbar support could be used.*

**Editor's Note.* Alternatively, some lightweight wheelchairs now have back angles of 8 degrees.

Armrest and Footrest Factors

Armrest Height: In a properly fitted wheelchair the client should not have to depend on the armrests for lateral support. Although the vertical support provided by the armrests can help reduce the load on the buttocks and thighs for a severely disabled client, this is an unlikely consideration for manual wheelchairs users.

In addition to supporting the arms, armrests provide a surface to push against releasing pressure for clients with insensitive skin. In conjunction with side panels, armrests provide protection for the clients' clothing from dirt and interference with the wheels.

The height of the armrest should be 1 inch higher above the floor level than the olecranon process (prominence of the elbow) with the arm pendant as the client is seated in the wheelchair (**Figure 8**). Many clients will not require armrests at all; however, for protection there should be some nominal barrier between the client and the wheel.

Footrest Length: The primary functions of the footrest are to provide support for the foot and shank, thereby reducing the load on the thighs, and maintaining the foot position. There must be at least a 2-inch clearance above the floor surface in order to prevent the bottoming of the footrest on uneven surfaces (**Figure 7**). Other physical constraints include caster clearance (360 degrees of caster swivel is necessary), and minimization of overall wheelchair length.

The load on the foot supports should approximate the weight of the foot and shank segments. Too little load will cause the feet to become dislodged from the supports on bumps or during quick changes in direction of the wheelchair. Too much load will increase the risk of pressure sores on the feet (primarily the heel). The weight of the shank and foot (one extremity) can be estimated as 4 percent of body weight or a value of 6 pounds. This adjustment can be made by grasping the foot and lifting until the heel appears to break contact with the support. This determination can be made by relating the "feel" of a 5-pound weight to the

Table 1.
Effects of Variations from Optimal Dimensions

Variable	Condition	Potential Adverse Consequence(s)
Seat position (fore/aft)	too forward	increased RR, SS; decreased PE, PAC, YAC.
	too aft	reverse of above consequences.
Seat height/axle position	too high or too low	reduced propulsion efficiency and limited mobility; decreased PAC.
Seat height/footrest	too short	increased pressure on both feet (heel) and buttocks (ischial tuberosities) resulting in an increased potential for pressure sores.
	too long	increased pressure on popliteal surface with potential for decreased circulation to leg and foot and greater potential for thrombosis, etc.
Seat width	too narrow	increased pressure on soft tissue with potential for pressure sores; interference with wheel.
	too wide	increased chair width resulting in potentially decreased access; lateral instability with potential for postural deviation (scoliosis); decreased control and PE.
Seat depth	too short	concentration of pressure on buttocks and feet (see Seat height).
	too long	compression of popliteal area (see Seat height).
Back width	too narrow	compression of lateral body surfaces against seat posts.
	too wide	lateral instability which can induce or exacerbate spinal deformity (scoliosis).
Back height	too high	restriction of shoulder mobility resulting in reduced control and mobility; restriction of aft rotation of the trunk resulting in less PAC.
	too low	fore-aft and lateral trunk instability with potential for spinal deformity (scoliosis, kyphosis, lordosis).
Seat angle	too shallow	forward displacement (sliding) which can result in poor posture and potential spinal deformity.
	too steep	concentration of pressure on buttocks; may put too much strain on hamstrings.
Back contour	too flat	reduced lateral support with potential for spinal deformity.
	too concave	not likely to pose a problem but will have an effect on functional seat depth and horizontal seat position.

perceived weight of the foot and shank in the above process. For tall clients, this positioning process may require a corresponding change in seat height and/or legrest angle due to the interdependence of these factors.*

Foot Plate Angle: The foot-to-leg angle should be approximately 90 degrees. This angle is common to most wheelchairs.

CONSEQUENCES OF IMPROPER MEASUREMENT

The further impact of ergonometric factors upon wheelchair performance is illustrated above.

**Editor's Note.* Footplates can now be ordered as 'forward-mounted' to accommodate extremely long leg length without raising the seat height from the floor. This will increase overall turning radius.

ACKNOWLEDGMENTS

The drawings for **Figures 1, 2,** and **4** through **8** of this article were done by Samuel R. McFarland, MSME. The photograph in **Figure 3** was provided by the University of Virginia Rehabilitation Engineering Center.

REFERENCES

1. **Brubaker CE:** Wheelchair prescription: An analysis of factors that affect mobility and performance. *J Rehabil Res Dev* 23(4):19-25, 1986.
2. **Brubaker CE, McLaurin CA, McClay IS:** Effects of sideslope of wheelchair performance. In *Proceedings of the 8th Annual Conference on Rehabilitation Technology* 5:81-85. Washington, DC: Association for the Advancement of Rehabilitation Technology, 1985.
3. **Brattgard CE, Grimby G, Hook O:** Energy expenditure and heart rate in driving a wheelchair ergometer. *Scand J Rehabil Med* 2:143-148, 1970.
4. **Brubaker CE, McClay IS, McLaurin CA:** Effect of seat position on propulsion efficiency. In *Proceedings of the 2nd International Engineering Conference on Rehabilitation Technology,* Ottawa, 12-14. Bethesda, MD: Rehabilitation Engineering Society of North America, 1984.
5. **Brubaker CE, McLaurin CA, McClay IS:** A preliminary analysis of limb geometry and EMG activity for five lever placements. In *Proceedings of the 8th Annual Conference on Rehabilitation Technology* 5:350-352. Washington, DC: Association for the Advancement of Rehabilitation Technology, 1985.