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Review

Aspects of Manual Wheelchair Configuration Affecting Mobility: A Review

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Abstract. Many aspects relating to equipment configuration affect users' actions in a manual wheelchair, determining the overall mobility performance. Since the equipment components and configuration determine both stability and mobility efficiency, configuring the wheelchair with the most appropriate set-up for individual users' needs is a difficult task. Several studies have shown the importance of seat/backrest assembly and the relative position of the rear wheels to the user in terms of the kinetics and kinematics of manual propulsion. More recently, new studies have brought to light evidence on the inertial properties of different wheelchair configurations. Further new studies have highlighted the handrim as a key component of wheelchair assembly, since it is the interface through which the user drives the chair. In light of the new evidence on wheelchair mechanics and propulsion kinetics and kinematics, this article presents a review of the most important aspects of wheelchair configuration that affect the users' actions and mobility.
Key words: Wheelchairs, Rehabilitation, Ergonomics

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INTRODUCTION

The use of a manual wheelchair suitable for a user's individual characteristics and needs can improve their independence, sense of participation and quality of life[1–3)]. Changes in the wheelchair configuration can affect propulsion forces, the range of motion (ROM) of the upper limb joints, rolling resistance and system stability. Ultimately, all these aspects determine how easy or difficult it is to propel a wheelchair in everyday mobility. System stability and mobility performance are two inter-related variables: improving one has an impact on the other. Accordingly, healthcare professionals have to find the best balance between stability and performance when prescribing a wheelchair. Consequently, understanding how the changes in wheelchair configuration impact a user's work and system stability is important for minimizing the demand on the upper limbs during manual propulsion and optimizing the user's mobility.

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Although a widely used assistive technology device, the wheelchair has been cited by many users as the main factor limiting their community participation[4)]. Indeed, the daily distance traveled and the average speed of wheelchair users are significantly lower than those of individuals without disabilities[5–9)]. Although quantifying the specific contribution of the equipment to this limited mobility is not possible, it is reasonable to state that the wheelchair design and mechanics play an important role in it. Furthermore, the distance traveled should not be thought of as the only variable representing daily mobility, since it does not reflect how people move but only how far people go. However, it does illustrate the existing gap between walking and wheelchair mobility.

Manual wheelchair propulsion exposes the upper limbs to a harmful combination of load and repetition, resulting in a high prevalence of shoulder abnormalities among wheelchair users[10–12)]. Since wheelchair users rely on their upper limbs for most daily activities, the presence of pain and injuries limits their mobility, independence and quality of life[13)]. Therefore, minimizing mechanical loads during manual propulsion and optimizing mobility efficiency must be addressed by researchers, manufacturers and clinicians in an attempt to improve overall mobility. In this context, the appropriate prescription is important in the provision of the most suitable equipment for a user's needs and expectations. Somewhat surprisingly, a recent study found that

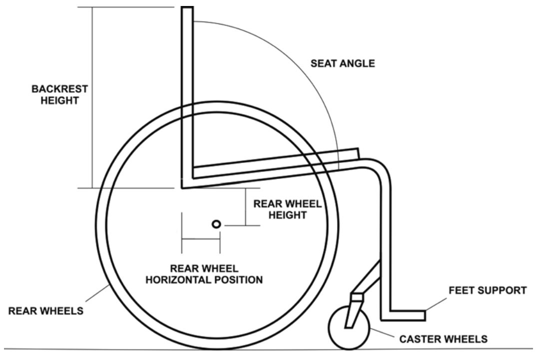

Fig. 1. Wheelchair configuration: factors that affect manual mobility

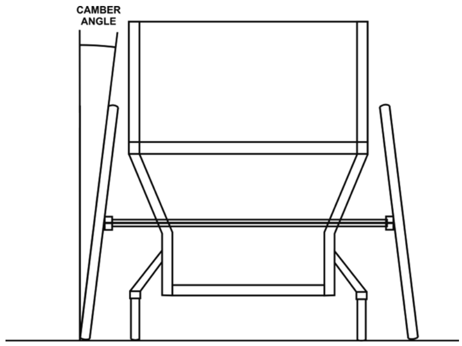

Fig. 2. Rear wheel camber (front view)

68% of the evaluated wheelchairs were not suitable for their users, and this may be interpreted as a result of prescription errors[14].

Many studies have investigated how different wheelchair configurations impact the biomechanics of manual propulsion. Seat angle and dimensions, rear wheels' vertical and horizontal position, and wheel size and camber have been shown to affect propulsion efficiency and wheelchair drivability[15–22]. In an effort to preserve upper limb function among wheelchair users, the Paralyzed Veterans of America Consortium of Spinal Cord Medicine[23] provided some guidelines for prescribing and adjusting a wheelchair in order to reduce the risk of developing injuries in to the upper extremities. However, recent studies have brought to light new evidence on the role of wheelchair configuration in wheelchair mechanics[24–26].

This review paper discusses the evidence on the aspects of wheelchair configuration affecting users' work and mobility. The review covers the most relevant aspects of the interaction between wheelchairs and users, updating current knowledge on wheelchair mobility with valuable information about research, development and innovation on wheeled mobility. Ultimately, clinicians, manufacturers and users may benefit from this study when prescribing, designing and selecting a wheelchair that provides the best mobility performance, comfort and functionality for the user.

WHEELCHAIR COMPONENTS AND CONFIGURATION

The most common aspects of wheelchair components and configuration indicated as affecting manual mobility are those related to the geometry of the system assembly, as shown in Figs. 1 and 2. In other words, the relative position of each component related to the others, and to the user, determines wheelchair mechanics, stability and the biomechanics of manual propulsion. The evidence related to each of these aspects affecting wheelchair mobility are presented and discussed below.

BACKREST HEIGHT

The backrest configuration influences the trunk support and upper limbs' ROM. These aspects are counterposed when one considers the two extreme situations: while a higher backrest provides greater support, it limits shoulder extension, which is particularly undesirable, since it is necessary to posteriorly grip the handrims of the wheel when starting to push a wheelchair. On the other hand, lower backrests allow the upper limbs to move freely, but back support and posterior stability are limited. Based on our clinical experience, most lightweight manual wheelchairs have backrests with a standard height of 400 mm.

A study by Yang et al.[27] found that a lower backrest (200 mm, versus the highest 406 mm) allowed greater shoulder ROM and greater push angle and push time, thus reducing push frequency. However, backrest height did not significantly affect the forces applied to the handrim. According to Cherubini and Melchiorri[14], users with impaired trunk control would benefit from higher backrests, which should be positioned 20 mm below the scapulae inferior angle. Those with intact trunk control should use lower backrests, taking the top of the lumbar spine as a reference. Since the seat configuration depends on the user's physical characteristics, the use of anatomical references seems to be the most appropriate approach, with the backrest height ranging from 200 mm to 406 mm, as proposed by Yang et al.

SEAT AND BACKREST ANGLE

Reclining the seat angle is a common procedure used to improve a user's sitting balance and functional reach, but it also affects the biomechanics of manual propulsion. The use of straight seat angles is related to the development of shoulder pain[28]. However, in terms of propulsion efficiency, the optimal seat inclination is still not known. Desroches et al.[29] showed that altering the seat angle (0°, 5° and 10°) and backrest angle (95°, 100° and 105°) did not influence the shoulder loads during manual propulsion by elderly wheelchair users.

The pressure on the seat interface is also an important concern for therapists when configuring the seat and backrest angles. The study by Park and Jang[30] did not report

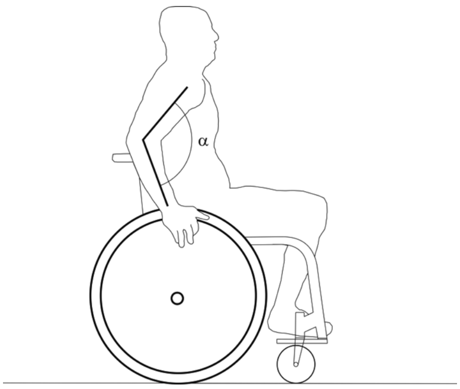

Fig. 3. Elbow angle (α) as a reference for the optimal vertical position of the rear wheels

definitive findings supporting the hypothesis that a reclined backrest (with an angle wider than 90° in relation to the horizontal line) reduces the pressure on the seat interface. Although a reduction in the pressure on the ischial tuberosity was found, there was an increase in the peak pressure on the sacrococcygeal region. Furthermore, the study of Maurer and Sprigle[31)] found no indication that increasing seat angle implies in increased seat interface pressure. Their results showed that less pressure was concentrated under the ischial tuberosities with increasing seat inclination, which seems to load slightly more body weight under the thighs and away from the ishcial tuberosities.

ANTERIOR–POSTERIOR AXLE POSITION OF THE REAR WHEELS

The anterior–posterior position of the rear wheels influences two important aspects of wheelchair mobility: stability and manual propulsion. While positioning the wheels rearward improves stability, it limits the user's ability to reach the handrims in this rearward position, thus reducing the push angle. Alternatively, moving the wheels forward improves propulsion biomechanics but reduces stability. The optimal position of the rear wheels is a client-dependent decision, based on the user's perception of stability and ease of chair propulsion. However, there are some objective guidelines to support this decision. The rear wheels should be positioned in the most forward position that does not compromise system stability[23)]. Gorce and Louis[16)] showed that, when moving the rear wheels forward, push angle and shoulder ROM are increased, thus reducing both push frequency and handrim forces, minimizing the risk of upper limb injuries[32)]. In addition to the biomechanical benefits, moving the rear wheels forward diminishes the wheelchair length and, as a result, facilitates turning maneuvers by reducing the rotational inertia of the system[24)].

VERTICAL POSITION OF THE REAR WHEELS

The vertical distance between the rear wheels and the seat greatly influences the biomechanics of manual propulsion. Having a lower seat benefits manual propulsion because it results in increased push angle. However, it results in increased upper limbs' ROM, which is potentially harmful if physiological limits are exceeded[33)]. On the other hand, when the user is too high above the wheels (i.e. in a higher seat), he/she can only push the handrims over a short distance (small push angle), and to maintain the desired speed, the user has to increase push frequency[34)], which may lead to muscular fatigue[32)]. The relation between seat height, push angle and push frequency has been investigated by Richter et al.[35)] and Wei et al.[36)]

The optimal seat height is determined by the elbow angle when the user holds the handrim at its top position (Fig. 3). Previous studies have shown that elbow angles ranging from 100° to 120° are related to improved propulsion efficiency and lower energy expenditure[37–39)]. Lower seat heights (elbow angles ranging from 80° to 90°) have been shown to be less efficient in terms of handrim forces and cardiorespiratory parameters[37)]. Therefore, in order to preserve upper limb function, it is recommended to set up the chair with the seat positioned at such a height that the elbow angle ranges from 100° to 120°[23)].

CAMBER OF THE REAR WHEELS

Stability is enhanced with wheel camber, especially when moving over lateral slopes. In addition, the hands are better protected against trauma because the wheels touch the floor spanning a wider area than the hands have in contact with the handrims. Maneuverability is also enhanced by wheel camber, which facilitates turning maneuvers.

Previous studies have investigated the effects of wheel camber on propulsion biomechanics. Camber angles wider than 15° increase the elbow ROM, reduce wrist radial deviation and increase wrist ulnar deviation[15)]. The changes in wrist kinematics are a consequence of the contact and release positions of the handrim happening in a more forward position. Camber angles ranging from 0° to 9° have been shown not to affect the cardiopulmonary parameters of manual propulsion[40)]. In addition, the average acceleration of the wheelchair is greater with 15° of camber, compared to cambers ranging from 0° to 9°[15)]. This finding is related to the increased rolling resistance generated by angles greater than 9°, which require the user to increase angular acceleration in an effort to maintain the average velocity[41)]. Rolling resistance is reduced by cambers up to 9°, compared to wheels with no camber[42)]. Perdios et al.[40)] indicate that 6° is the optimal angle for rear wheel camber, in terms of lateral stability in inclined planes, comfort during handrim propulsion, maneuverability and the general preferences of manual wheelchair users. However, rear wheel camber increases the system's overall width, which may lead to problems when moving in tight spaces.

FRAME MATERIAL

The frame mass plays an important role in the mechanics of a manual wheelchair. Ultra-light chairs are most appropriate for those users who have an active lifestyle, since the reduced mass helps with the preservation of upper limb function by reducing the handrim forces during manual propulsion[23]. Aluminum is widely used in wheelchairs, since it has a better strength-to-weight ratio than steel and does not require special manufacturing techniques[43]. More recently, titanium and carbon fiber have been used to make wheelchair frames. Titanium has advanced properties in terms of absorbing shocks and vibration, and a better strength-to-weight ratio than aluminum[44]. Similarly, carbon fiber has an improved strength-to-weight ratio, and the fibers can be molded in a way that increases the strength in one direction while increasing flexibility in another direction. However, both titanium and carbon fiber are significantly more expensive than aluminum, and they also require specialized manufacturing techniques[44].

FRAME DESIGN

Currently, two types of frame design are commercially available: folding and rigid frames. When selecting the frame type, one should consider the user's functional and physical features and lifestyle. For a less active user, wheelchairs with folding frames may be the best choice, since they are, in general, larger and therefore more stable, and allow disassembly of components that may facilitate transportation. Moreover, Liu et al.[43] showed that folding-frame wheelchairs are more stable in the forward direction, and they suggested that this may be a consequence of the footrest position being more forward in folding chairs than in rigid-frame wheelchairs. Rigid frames, in turn, are generally lighter and provide improved mobility performance, but stability is affected.

WHEEL TYPE

The design of the rear wheels plays an important role in the system's mass and vibration transmission. From a mechanical standpoint, heavier wheels make it harder to start moving from a standing position; lighter wheels allow users to accelerate faster[45]. Furthermore, because the rear wheels are located on the outer side of the chair, the mass greatly influences the rotational inertia of the system[24]. Although users have reported improved comfort in manual propulsion with lighter wheels, Hughes et al.[45] found no influence of the wheels' weight on energy expenditure during manual propulsion using two pairs of wheels differing by 0.6 kg.

Traditionally, rear wheels have been produced in either plastic or steel. More recently, carbon fiber has been used to produce lighter wheels. In addition to weight reduction, carbon fiber wheels minimize the transmission of vibration to the user's body[44], which is highly beneficial since vibration may cause discomfort, nausea, dizziness, fatigue and even exacerbate muscular hypertonicity and pain[45].

TIRE TYPE

When selecting rear wheel tires, two options are available: pneumatic and solid tires. Pneumatic tires provide good impact and vibration absorption, thus improving users' comfort[46]. Solid tires, however, are still commonly used because they require almost no maintenance, and pose no risk of emptying due to punctures[25].

An important aspect of the tire type affecting wheelchair mobility is the force opposing the movement of the tire rolling on a surface. This force, known as rolling resistance, is dependent on the tire design, material composition, mass of the tires, and interactions with the surface. Pneumatic tires have been shown to significantly reduce rolling resistance compared to solid tires[25], and this facilitates manual propulsion by keeping the wheels rolling for a longer distance until another push is need, thus contributing to mobility efficiency.

CASTER WHEELS

Caster wheels are important components of the system, influencing the system's stability, rolling resistance, maneuverability and users' comfort. Similar to the rear wheels, pneumatic and solid caster wheels are commercially available. Although pneumatic wheels have been shown to reduce rolling resistance, they do require extra attention regarding pressure control and maintenance. Therefore, solid casters are still the most commonly used type of caster in manual wheelchairs.

Caster wheels and stem assembly can influence a wheelchair in motion in many aspects. First, the diameter of the caster wheels affects rolling resistance: smaller wheels increase rolling resistance, thus requiring the user to push harder to maintain an average velocity. The position of the caster assembly in the wheelchair geometry is also an important aspect of wheelchair mechanics. The shorter the distance between the rear wheel and caster, the lower the rolling resistance due to the increased weight upon the rear wheels[44]. Furthermore, more mass is located near the center of the system and, therefore, rotational inertia is reduced, making turning maneuvers easier. However, this requires reduced wheelchair length, which may have an impact on system stability.

Finally, the transmission of shock and vibration is an important aspect of the casters' size and composition. Smaller casters with solid tires have limited shock and vibration absorption and, therefore, the user's comfort is affected. In an effort to reduce vibration and improve user's comfort, damping materials may be used inside the casters' stem[44]. Similarly, the use of suspension in the casters' assembly is an efficient way of reducing vibration transmission to the user[47].

LEG AND FOOT SUPPORT

The consequences of inappropriate positioning of the leg and foot support are felt in relation to the pressure on the seat interface, the user's comfort and stability, maneuverability, and the mechanical parameters of the wheelchair. When the foot support is too low, the pressure on the seat interface tends to increase, since the weight of the legs and feet pushes the thighs down, compressing them against the seat. Because the feet are not properly supported, gravity makes the ankles bend down, facilitating the shortening of the calf muscles. In addition, without proper anterior support for the feet, reaching forward becomes an unstable and dangerous task[48]. In turn, when the foot support is too high, the thighs are not completely supported by the seat, which may increase the pressure on the buttocks.

The horizontal distance between the leg and foot support and the rear wheels determines mass distribution and the overall length of the wheelchair and, in consequence, the inertia of the system. The variables directly affected by the positioning of the leg and foot support are the system's center of mass, stability, rolling resistance and moment of inertia, with all these variables influencing wheelchair stability and maneuverability[3, 26].

The angle of the knees can be used as a reference for positioning of the foot support. In general, the foot support is positioned in such a way that the angle of the knees ranges from 90° to 120°[49]. MacPhee et al.[26] investigated the effect of two extreme angles of the knees − totally extended (0°) and totally flexed (120°) − on the mechanics of the wheelchair. When the knees were totally flexed, the wheelchair length was reduced by 39%, the center of mass moved backwards 38% and rolling resistance was reduced by 21%. MacPhee et al.[26] suggested that the rolling resistance is reduced by the center of mass being moved backwards, which increases the mass upon the rear wheels, thereby reducing the mass upon the casters. Furthermore, the moment of inertia of the system was reduced by 42% when the knees were totally flexed. This is a relevant finding, since the moment of inertia directly influences wheelchair maneuverability. Indeed, the angular velocity increases by 40% when turning on its own axis (i.e. a zero radius turn), and subjects found it easier to turn the wheelchair with their knees totally flexed.

HANDRIM DESIGN

As the interface through which the user drives manual wheelchairs, the handrims play an important role in terms of both the comfort and efficiency of manual propulsion. In the majority of manual wheelchairs, the handrims are two metallic round tubes of 20 mm diameter, located on the outer side of the wheels. The small size of conventional handrims leads to two main problems: increased pressure on the areas of the hands' surface where contact with the handrim occurs; and reduced mechanical efficiency due to inability to hold the handrim with the entire hand, which requires additional muscle contraction to stabilize the hands on the rim[50]. Not surprisingly, many wheelchair users hold the handrim and tire simultaneously when propelling the wheelchair[51].

Previous studies have proposed different handrim designs in order to optimize propulsion comfort and efficiency. Van der Linden et al.[52] found that handrims with a greater tube diameter showed greater efficiency and lower physiological costs. Improvements in upper limb symptoms were found with the use of the Natural-Fit (Three Rivers Holdings, Mesa, AZ, USA), a commercially available product designed to provide an improved fit to the hand and relieve stress on the carpal tunnel[53]. Richter et al.[54] found reduced finger and wrist flexor activity during manual propulsion with the use of a flexible handrim, a metallic tube connected to the wheels through a flexible rubber membrane that reduces peak forces during initial contact. In a recent study, wheelchair users reported improved comfort and maneuverability with an ergonomic handrim that offers an increased surface for hand contact based on human anthropometric features[55].

CONCLUSION

Improving the mobility efficiency of wheelchair users has been a challenging goal for researchers and professionals. Manual wheelchair mobility is affected by factors that are intrinsically related to wheelchair design and configuration. This paper collated the evidence on how different configurations influence the extent to which the wheelchair meets the needs of users. By changing the wheelchair configuration, it is possible to optimize the biomechanics of manual propulsion, system stability, pressure on the seat interface and the user's perception of comfort and wheelchair drivability. However, manual propulsion is still very demanding on users and much less efficient than normal gait. Further studies should investigate how wheelchair configuration affects the biomechanics of manual propulsion during different maneuvers, trajectories and situations most representative of mobility in daily life. This knowledge may help both manufacturers and clinicians when designing and prescribing wheelchairs that are more appropriate to users' functional features, needs and expectations, thus benefiting users' social participation, independence and quality of life.

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