Reaching for Independence: Challenges for a New Concept of Wheelchair Design

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Reaching for Independence: Challenges for a New Concept of Wheelchair Design

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1. Introduction

The wheelchair has been used for many years as the main means of mobility for many people who have diseases or conditions leading to movement impairment. As an assistive technology device, the wheelchair aims to improve locomotion and promote functional independence, allowing the user to perform his/her activities of daily living (Scherer & Cushman, 2001). Although being one of the most used mobility technology, the wheelchair is still referred by users as the main limiting factor in community participation (Chaves et al., 2004).

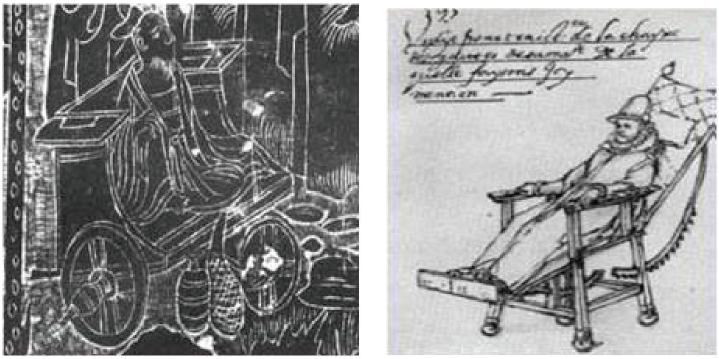
Why does the wheelchair, as mobility equipment, fail in providing full independence to its users? To understand this limitation, several factors must be considered. Studies have shown high prevalence of pain among wheelchair users, which negatively affects their quality of life and increases their dependence of caregivers (Desroches et al., 2008; Boninger et al., 2004). The pushrim propulsion has been shown to contribute to the development of upper limb overload injuries, mainly due to its mechanical inefficiency (Van der Woude et al., 2001). Equally important, cost and specific features of the equipment such as weight, size, structure and appearance can also determine the success of its use.

So, what can be done to improve the wheelchair design in terms of performance, comfort, functionality and accessibility in order to provide the user full independence? For doing so, it is crucial that the design of the equipment considers not only the users' age, physical and motor conditions, but also their preferences, lifestyles, work, leisure and sport activities, users' history, and finally, their future objectives (Scherer, 2002; Trefler et al., 2004). Recently, alternative modes of wheelchair ambulation have been proposed. However, pushrim propulsion still remains the main mean of wheelchair ambulation, which exposes users' difficulties in adapting to different systems with changes in wheelchair configuration and dimensions.

Over the last years, bioengineering and ergonomics research have successfully generated evidence base for developing wheeled-technology, ergonomic design and fitting procedures, which has significantly contributed to this purpose. Despite of it, the wheelchair technology remains remarkably old-fashioned compared to other mobility technologies already well-established in daily life. This study was aimed at presenting a critical review of wheelchair research and development, focusing on the analysis of how equipment features can determine the success or failure of its use.

2. An overview of the wheelchair evolution

Looking at historical records enables the understanding of the evolution of wheeled mobility devices, as well as the adaptations and innovations in face of individual needs. The first image of a seated mobility device was found in a Chinese sarcophagus dating from 525 A.D (Figure 1a). A wheelchair with footrest was designed for the King Phillip of Spain in the sixteenth century as an adaptation to his throne due to his rheumatic disease (Figure 1b).



(a) (b)

Fig. 1. Wheelchairs: (a) image found in a Chinese sarcouphagus (525 a.C.); (b) King Phillip´s throne adapted with a footrest (XVI century). Source: Sawatzky.

In 1655, Stephen Farfler built a wheelchair propelled by the user himself using the upper limbs. This equipment was the precursor of what we know as hand-cycling. Although different from the current wheelchairs, it represented an important advance as the user could control his/her locomotion, thus enabling the user to be socially reintegrated (Figure 2).

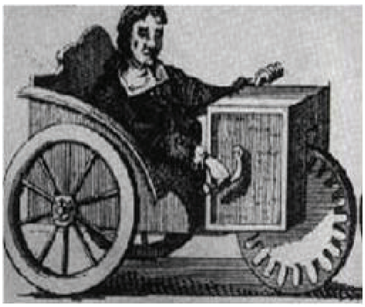
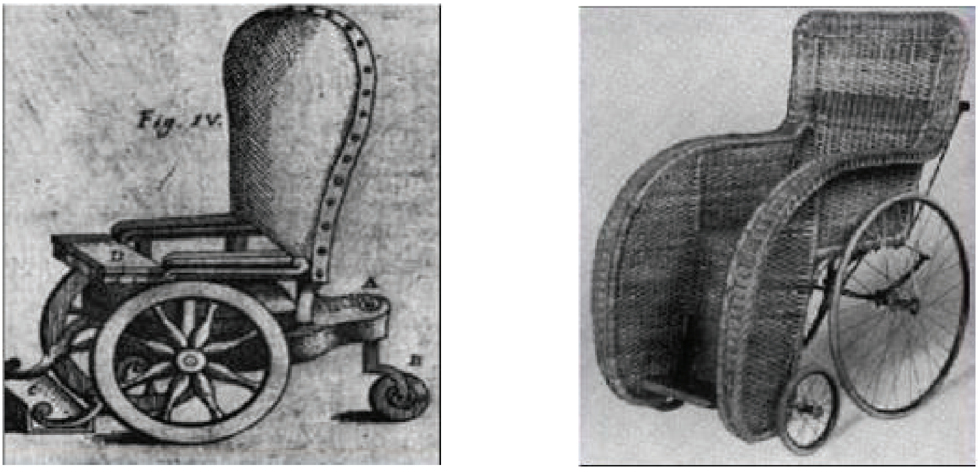


Fig. 2. Self-propelling wheelchair (1655). Source: Sawatzky.

In the eighteenth century, the new wheeled mobility devices began to show a clear concern for the user's comfort. Figure 3a shows the representation of a wheelchair with reclining backrest and footrest-height adjustment. In 1916, a wheelchair made of Indian straw had two notable innovations: its lower weight due to the lighter manufacturing material and its configuration with big rear wheels and small front wheels (Figure 3b).



(a) (b)

Fig. 3. Wheelchairs: (a) reclining backrest and footrest adjustment (XVIII century); (b) larger rear wheels and reduced weight due to the use of Indian straw (1916). Source: Sawatzky.

In 1933, Herbert A. Everest, an american who became paraplegic due to a disease, in partnership with the engineer Harry C. Jennings, developed a wheelchair with flexible seat, folding structure made of steel tubes, and pushrim on the rear wheels (Figure 4). This concept of wheelchair remained throughout the last century, still representing the standard model from which other improvements are proposed despite the lack of significant conceptual changes.

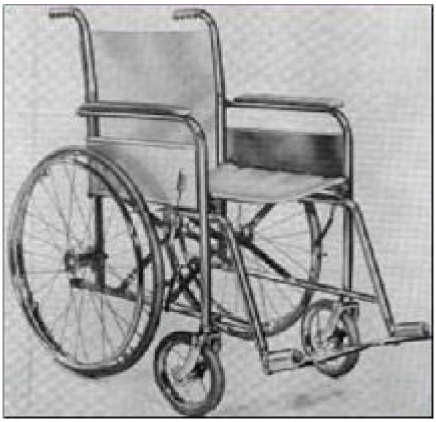


Fig. 4. Mettalic folding structure (1933). Source: Sawatzky.

Through the years, it can be noted some factors determining changes in the design of wheelchairs. Among these factors, one can cite the introduction and popularization of automobiles, which increased the number of car accident victims, most becoming wheelchair-dependent. In addition, the wheelchairs need to be transported in vehicles. The development of rehabilitation programs and improvement in medical services, including the growing number of disabled individuals and the emergence of adapted sports, have favored the development of more sophisticated equipment to better meet the needs of wheelchair users. After the 1948 Paralympic Games in England, the concern was to find lighter materials and meet requirements of versatility and usability for a better sporting performance (Figure 5).

Fig. 5. "*Champion 3000*", sport wheelchair (1986). Source: Carriel, 2007.

3. Injuries related to manual wheelchair propulsion

To fully understand the problems involved with prolonged used of manual wheelchairs, it is worth noting that the upper limbs no longer function as before because the loss of motor function in lower limbs causes the upper limbs to perform the task of locomotion. Manual propulsion is the primary means of mobility for wheelchair users, comprising two distinct phases: propulsion phase (or impulse), where there is full contact between hands and push-rims, and recovery phase, where the hands leave the pushrim and swing back to start new contact for another propulsion, thus being characterized as a highly repetitive task (Boninger et al., 2000). Ideally, the recovery phase should be almost entirely done without muscle activity, but differences in wheelchair design and configuration as well as in propulsion technique may contribute to an active recovery phase, adding work load to shoulder muscles. Thus, manual propulsion requires the user to adjust to a particularly stressful work for the upper limb muscles (Wei et al., 2003).

As a result of years of manual wheelchair propulsion, it is believed that the active muscles during the push phase become stronger, while the muscles involved in the recovery phase remain with the same force, creating a muscle imbalance in the shoulder joint (Ambrosio et al. 2005; Mulroy et al., 1996). In addition, the muscles that play an important role in stabilizing the shoulder (rotator cuff, deltoid and long head of biceps) may be changed due to the repetitive nature of wheelchair propulsion (Burnham et al., 1993, Miyahara et al. 1998).

Upper limb pain is a highly prevalent complaint among manual wheelchair users. The study by Sie et. al (1992) found a prevalence of 64% of upper limb pain in persons with paraplegia, with shoulder being the most frequently mentioned site (32%). Curtis et al. (1999) found that 42% of wheelchair users report shoulder pain. Moreover, carpal tunnel syndrome (CTS) has been commonly diagnosed in people who use manual wheelchair. The incidence of CTS in this population ranges from 49% to 63% (Aliure et al. 1985; Gellman, 1988; Tun and Upton, 1988, Davidoff et al. 1991; Steadward and Burnham, 1994; Sie et al. 1992).Furthermore, a correlation was demonstrated between median nerve function and the propulsion rate: higher cadence and larger forces applied to the pushrim are related with reduced median nerve function (Boninger et al., 2004). In addition, ulnar nerve injury has also been reported (Tun and Upton, 1988; Steadward and Burnham, 1994). In consequence, upper limb pain has been associated with poorer quality of life and increased dependence (Boninger et al., 2004, Subbarao et al., 1995).

Several factors may contribute to upper limb injury among wheelchair users, such as body weight and prolonged wheelchair use (Boninger et al., 1999). In addition, it has been suggested that the repetitive and selective activity of muscle groups contributes to the development of a muscle imbalance in the shoulder joint (Myamahara, 1998). Such consequences of the wheelchair propulsion can induce a potentially harmful condition, since wheelchair users rely on their upper limbs for mobility, transfers and most activities of daily living. Understanding the mechanisms involved in this alteration of the upper limbs' mechanics is, therefore, essential to find solutions that minimize or eliminate the risk inherent to the manual use of the wheelchair.

4. Critical analysis of the wheelchair as mobility equipment

Conceptually, a manual wheelchair aimed at promoting independent mobility should consider performance, safety, comfort, independence, and transport ease, besides not being harmful to the upper limbs. Despite the diversity of current models and proposed improvements, an equipment covering all these aspects has not been developed yet. In all proposed solutions, improvement in one aspect leads to the impairment of another, which generally limits the acceptance by users. As a result, manual wheelchair propulsion still remains the most widely used form of locomotion among wheeled mobility technologies.

Manual wheelchairs have limitations that make it difficult for the user to reach full independence. Firstly, going uphill is almost impossible due to both the difficulty of propelling and the risk of the wheelchair toppling over, causing the user to fall down. Thus, the user needs the help from another person. Another difficulty is to move around for relatively long distances, because this task requires long-term activity with relatively high frequency use of the upper limbs, causing fatigue and discomfort. The most immediate solution to both problems listed above is the to use a motorized wheelchair. However, although it enables the user to move over long distances and on slopes, the motorized equipment makes the user a "passenger," in a passive condition, resulting in the risk of weight gain and development of cardiovascular disease. In addition, the motorized wheelchairs have higher cost, weight and difficulty in transporting it.

Despite being equipment for promoting mobility, the wheelchair is perceived by the users as the main cause of their limitation at and away from home (Keys et al., 2003). Surprisingly, users find the wheelchair more limiting than their own physical and functional condition. The main complaints are related to weight and higher dimensions of the equipment, making it hard to maneuver, especially in places where space is restricted (Post et al., 1997). In accordance to this statement, Mann et al. (1997) found that 26% of the problems with a wheelchair were related to its weight and size: too heavy to push, too wide to use inside the home.

5. Autonomous wheelchairs

The propulsive mechanism of a mobility equipment can be obtained by several resources, including the explosion of fuel, pneumatic system and electric motorization, the latter being the representative of the vast majority of autonomous wheelchairs.

Selecting a wheelchair is a major and complex decision for people with limited mobility. For certain populations with specific functional conditions, there is no clear recommendation for wheelchair prescription regarding mobility mode: manual or powered wheelchair. Thus, the pros and cons of both types of wheelchairs must be considered when choosing the best mode of mobility, depending on the personal lifestyle and preferences, home environment, community accessibility and functional needs (Cooper et al., 2002). Patients with low cervical spinal cord injury typically face this doubt when selecting a wheelchair. The very recent study of Hastings et al. (2011) found that Individuals with C6 and C7 tetraplegia who use manual wheelchairs had significantly better physical function, mobility, and a higher employment rate than those who use power wheelchairs (Hastings et al., 2011). Although the important findings of Hastings et al. (2011) point in the direction to the use of manual wheelchairs, the great diversity among wheelchairs users highlights the need for a customized view of individual's features and needs when prescribing the equipment.

Eletric-powered wheelchairs (EPWs) have been shown to provide independence mobility for children with disabilities (Butler et al, 1982). Understanding the driving behavior of users of electric-powered wheelchairs is critical for designing EPWs, wheelchair components, battery (Cooper et al., 2002). However, when prescribing a powered wheelchair to children, some problem areas can be identified: education of the child about wheelchair usage and drivability, education of the general public about the use of the wheelchair on community spaces and public transportation systems, safety of the users and general public, and establishment of legal status for wheelchair ambulation (Breeed; Ibler, 1982). These factors are critical for a safe and successful usage of EPW and must be taken into account when selecting the equipment.

The advantages of EPW are related to the requirement of very little of the user's strength and endurance which, however, may not be desirable in all instances (Geisbrecht et al., 2009). Physical inactivity seems to contribute to obesity and a cycle of deconditioning and functional decline (Cooper et al., 1999). Furthermore, the weight of the devices (typically 150 lbs or greater) and difficulty in transporting are also limitations of EPW (Geisbrecht et al., 2009; Levy et al., 2004) which, therefore, require expensive vehicle modifications and mechanical lifts (Levy et al., 2010). . In addition, as any electrical equipment, powered wheelchairs have specific issues that can affect overall mobility. Studies have shown a wide disparity in the performance of the batteries and also the performance of the battery chargers of powered wheelchairs (Fisher et al., 1988; Garrett et al, 1990).

Finally, considering that one of the main objectives of an EPW is to provide greater mobility than manual wheelchairs, it is notably surprising that, in terms of daily distance traveled, there is no well-established difference between the two modes of wheeled mobility: while adult manual wheelchair users showed mean daily distance traveled of 1877+1131 meters (Oyster et al., 2011), adult electric-powered wheelchair users were reported to drive an average of 1667 m/day (Cooper et al., 2002). Thus, the motorized equipment does not solve the limitations found in manual wheelchairs related to the amount of mobility, and as a result highlights the need for innovative solutions for wheeled mobility devices.

6. Alternative modes of wheelchair propulsion

Alternative modes of wheeled mobility have been proposed in an attempt to enhance the performance, increasing functionality and independence of the users. The hub-crank propulsion system, through which a handle connected to the hub of the rear wheels allows for continuous movement of the hands around the wheel axle, required less effort and showed greater efficiency when compared the pushrim wheelchair propulsion (Van der Woude et al., 1995a; Van der Woude et. al., 1995b; Van der Vlies et al., 1999). To justify the good results, it is believed that the propulsive force exerted by the hands corresponds to only 20% of the cycle, whereas the hub-crank propulsion allows the hands to exert continuous pushing and pulling force through the handle around the hub of the wheel. Thus, both the flexor and extensor group of muscles are involved in the movement cycle, with better distribution of the muscle workload, thereby reducing the amount of work per unit (Van der Woude et al., 2001). However, the use of the hub-crank propulsion wheelchair has been restricted to outdoor environments because of the difficulty in maneuvering it in tight spaces due to its larger width (Van der Woude et al., 2001).

Another proposed solution is the use of lever propulsion systems, in which the arms move cyclically, synchronously or asynchronously. Propulsion systems equipped with a gear on the rear wheels have been recently developed, allowing the wheelchair to be controlled by an activation mechanism located at the top of the lever where the user's hand keeps in contact (Figure 6). Lever propulsion systems have been described as more efficient, requiring less physical effort compared to the pushrim propulsion (Engel et al., 1976; Van der Woude et al., 1993; Van der Woude et al.., 1997). Also, Requejo et al. (2008) found that the use of wheelchair with lever propulsion system reduced and altered the demand for work on the shoulder muscles. Woude et al. (2001) consider the lever propulsion system an interesting alternative for outdoor use, although it can also be used internally, especially for those wheelchair users with lower exercise capacity or those who need to move over greater distances. However, maneuvering and moving with a wheelchair equipped with levers in tight spaces is still a problem that limits its widespread use.

Fig. 6. Lever propulsion system (Requejo et al., 2008)

Stationary arm-crank ergometry has been highly used in exercises for upper body (DiCarlo et al., 1988; Wicks et al., 1983; Sawka et al., 1980), being shown to be a more efficient propulsion mechanism than the hand-rim propulsion (Tropp et al., 1997; Martel et al., 1991). Based on this concept, the arm-crank tricycle propulsion, also called hand-cycling, has become popular in wheeled mobility devices for daily life use and sports (Figure 7). Both synchronously and asynchronously, there is a continuous use of the arm and trunk muscles. However, although hand-cycling wheelchair seems to be the most appropriate mobility system for outdoors, its large dimensions make maneuverability in tight spaces difficult, thus limiting its overall use.

Fig. 7. Hand cycling (Valent et al., 2009).

In the study by Mukherjee et al. (2005), four distinct propulsion systems (pushrim, arm-crank using both arms, arm-crank using one arm and arm lever) were compared in terms of physiological variables (oxygen consumption – VO2 and heart rate). Although no difference had been found, and authors suggested that wheelchair users might have developed certain self-regulatory mechanisms in order to overcome the variation induced by the different propulsion systems.

7. Wheelchair engineering: The emergence of an integrative approach

Research and development of wheelchair involves different areas of knowledge so that the perspective of the interaction between body, human movement and equipment's design can be addressed as a whole, with the wheelchair being an extension of the user's body. Woude et. al. (2005) present three important areas in the research and development of wheelchair: mechanics of the equipment, human movement system, and user-wheelchair interface. Thus, it is important not only to adress both disciplines, but also their interaction as this depends on the success use of technology in favor of the user. Because of this multidisciplinary knowledge, the responsibility in conducting research and development of wheelchairs should be shared between health professionals (mainly physical and occupational therapists) and engineers (Mikołajewska; Mikołajewski, 2010). The first evaluate the equipment according to the functional needs of the patient and the latter seek to meet such needs and optimize the functionality of the equipment. Working together, health professionals and engineers can maximize the potential of interaction between humans and equipment.

At this point, it is worth returning to the question that guides this study: Why, compared to the technologically advanced products in a variety of areas, is wheelchair evolution so limited? The technological evolution of the wheelchair has not yet optimally gathered in a single project the three major areas presented by WOUDE et al. (2005): mechanics of the equipment, human movement system, and user-wheelchair interface. Although the use of lighter and stronger materials provided equipment with lower weight, better reliability and durability, the manual locomotor system remains unchanged as high loads are exerted on the upper limbs, which originally were not prepared to develop this function. The advent of the motorized wheelchair seems to solve this problem, but it also involves the imposition of a sedentary life, which increases the risks to the user's health.

The emergence of a special model of care, focused on patients with limited mobility, is essential to reach the advances needed in both healthcare and research and development of mobility equipment. For this new thinking, not only the knowledge of engineering and health should be taken into account, but the frontiers among the disciplines should be trespassed in order to create an open science, with fertile ground for boosting creative thinking. Furthermore, psychological condition, family dynamics in which the patient is inserted, and social relations should also be understood as factors inherent to the patient´s life. Likewise, an insight into work activities and socio-economic conditions favors the understanding of the condition in which the patient lives, thus allowing the equipment to be more appropriately adjusted to this context. Finally, the history of the patient's life is equally important. This includes the patient's expectations, frustrations as well as skills, leisure and sport activities, which make up a range of highly relevant information for determining the ideal equipment capable to promote acceptance and satisfaction. Figure 8 shows a schema of the integrative approach to the wheelchair user.

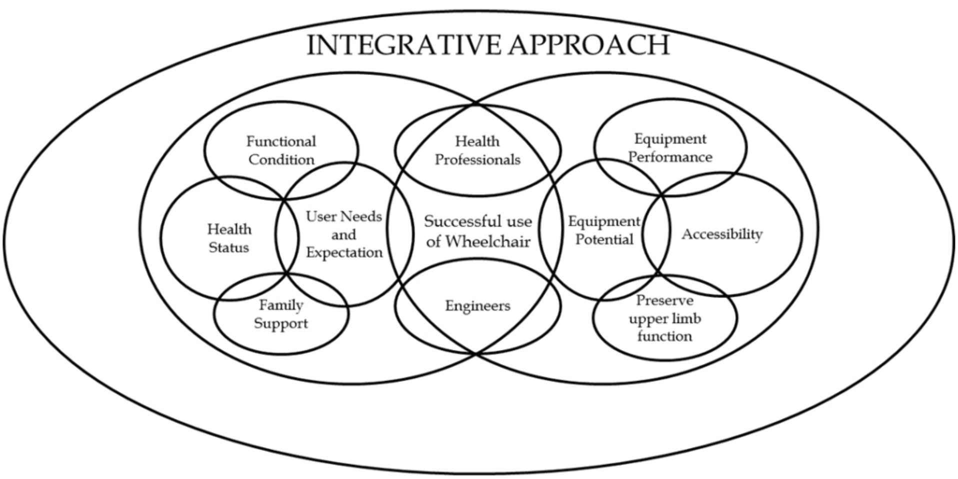


Fig. 8. Model of an integrative approach to the wheelchair user.

8. Ergonomics of the wheelchair pushrim design: A case study

As the interface by which the user drives the wheelchair, the pushrim plays a determinant role in the user's ability to control the wheelchair. The conventional pushrim, found in the majority of manual wheelchairs, is made of circular metal tubes located at a distance of 20 mm from the wheel. The tube diameter (20 mm) of these push-rims is too small for adults, whose hand length is approximately 180 mm (5). In consequence, the contact area between hand and pushrim is limited, leading to an increased pressure on the contact points of the delicate structures of the hand (Figure 9). Furthermore, the inability to hold the pushrim with the entire palm and fingers reduces the mechanical efficiency, as more muscle activity is required to stabilize the hand instead of promoting power for propulsion of the wheelchair (Van der Woude et al., 2003).

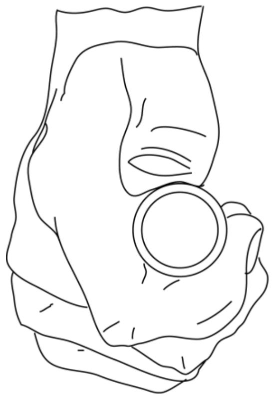


Fig. 9. Cross-sectional view of conventional pushrim (Medola et al., 2011).

It is noteworthy that wheelchair users often report that the design of the pushrim does not fully meet their needs during wheelchair propulsion, and in a survey with manual wheelchair users, only 39% reported using solely the pushrim for propulsion, and the majority (54%) reported holding both the pushrim and tire simultaneously (Perks et al., 1994).

8.1 An ergonomic approach

Based on ergonomics concept, a new design of wheelchair pushrim must have, firstly, larger contact surface without increasing wheelchair's dimensions. Also, the shape of the new pushrim must be proper to a comfortable and secure hand grip. In order to reach this goal, the new device features a slightly curved upper surface on which the thumb, the thenar eminence, and the base of the hypothenar eminence can rest; a lateral surface to support the distal half of the palm and proximal phalanges of fingers II, III, IV and V as well as a lower surface to support the medial and distal phalanges of the fingers are also available. Based on these features, a preliminary proposal for a new design of the wheelchair push-rim is shown in Figure 9a. In contrast to the conventional pushrim (20 mm diameter), which provides 68.8 mm of contact surface, the new pushrim was designed with approximately 123 mm of surface for hands with a length of approximately 180 mm (Pheasant & Haslegrave, 2006). This design leads to a better posture of the hands for a proper control of the wheelchair, thus allowing the hands to be fully supported for a stable, firm and functional grip (FIGURE 10)

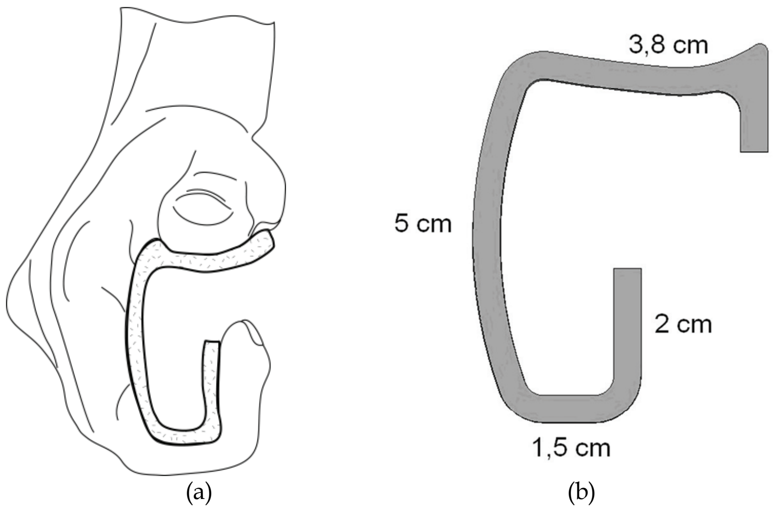


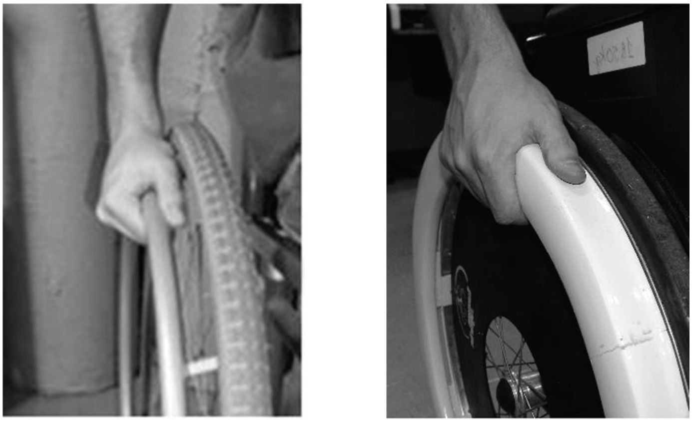
Fig. 10. Applying ergonomics: (a) preliminary proposal for the pushrim design; (b) defined project: shape and dimensions (Medola et al., 2011).

As for any hand operated device, the material used should provide both thermal comfort and adequate friction for the hands. In general, metallic materials should be avoided because they mechanically compress the tissues of the hand and increase the transmission of cold, heat and vibration. Conversely, in addition to the high stiffness and resistance to deformation under load, polymers offer a gain in comfort during wheelchair use by reducing the sensation of heat on the user’s hands. For these reasons the polyurethane was used to develop the pushrim prototype (Medola et al., 2011).

8.2 Preliminary results of the ergonomic wheelchair pushrim

Some features of the ergonomic pushrim really contributed for an improvement on its design and, therefore, will be briefly described. First, the larger surface contact positioned the fingers with a less flexed posture than the conventional pushrim. Furthermore, the convex shape of the lateral surface provided adequate support for the entire palm, requiring less effort of the fingers to hold the pushrim. Figure 11 shows the positioning of the hand in the pushrim, without the excessively flexor posture of the fingers as observed for the conventional pushrim. It can also be noted that the thumb has a proper support in the upper surface of the new pushrim. By using the space between push-rim and wheel, the new device was able to provide adequate support to the thumb without, however, increasing the width of the wheelchair, which could make it difficult to reach tight spaces.

Thus, with an innovative design, the ergonomic approach showed to be potentially beneficial for the old concept of wheelchair pushrim. The use of anthropometrics in the pushrim design allowed the development of a prototype suitable for a firm and stable hold, by providing a larger contact area between the hand and the device, thus reducing the effort of the fingers to hold the pushrim (Medola et al., 2011).



(a) (b)

Fig. 11. Hand coupling to: (a) conventional pushrim; (b) ergonomic pushrim. (Medola et al., 2011).

9. Conclusion

By observing the evolution of the wheelchair as mobility equipment over time, it can be noted that the user's individual needs have led to the creation of equipment with characteristics based on a concept of a wheelchair that, for nearly a century, has been widely used as the technology available for people with mobility problems. However, the manual wheelchair propulsion imposes a condition potentially harmful in long term use, which can cause the upper limbs to fail in promoting independent mobility. In an attempt to minimize or even eliminate the adverse effects of using the manual wheelchair, several devices have been created with important improvements in design and pattern of muscle work of the upper limbs. Because the equipment's size and weight affect the user's mobility in tight spaces and make it difficult to adapt to new techniques of upper limb movement, these devices have their overall acceptance limited and thus the pushrim propelled wheelchair remains as the main wheeled mobility device. Finally, we present a model for a new approach to rehabilitation engineering, based on a holistic view, that integrates patient, equipment and environment. The holistic framework for the integrated work between health professionals and engineers favors the emergence of creative solutions to major problems found in the current concept of manual wheelchair. The emergence of the integrative concept will also contribute to research, development and, consequently, production of scientific knowledge that goes beyond the very narrow limits of the disciplines, creating a unique and integrated science between the different knowledge areas.

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