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Literature Review

Alternative Modes of Manual Wheelchair Ambulation
An Overview

ABSTRACT

van der Woude LHV, Dallmeijer AJ, Janssen TWJ, et al: Alternative modes of manual wheelchair ambulation: An overview. *Am J Phys Med Rehabil* 2001;80:765–777.

An estimated 90% of all wheelchairs are hand-rim propelled, a physically straining form of ambulation that can lead to repetitive strain injuries in the arms and, eventually, to secondary impairments and disability. Further disability in wheelchair-dependent individuals can lead to a sedentary lifestyle and thereby create a greater risk for cardiovascular problems. Studies on lever-propelled and crank-propelled wheelchairs have shown that these propulsion mechanisms are less straining and more efficient than hand-rim–propelled wheelchairs. This article reviews these studies and substantiates that the frequent use of these alternative propulsion mechanisms may help prevent some of the secondary impairments that are seen among today's wheelchair-user population.

Key Words: Work Capacity, Wheelchairs, Mobility, Lever Propulsion, Hand Bike, Tricycle, Overuse Injuries, Fitness

With over 90% of all daily wheelchairs being hand-rim propelled,[1] hand-rim wheelchair propulsion has dominated wheelchair sports as well as daily wheelchair use. Hand-rim propulsion is inefficient and very stressful to the musculoskeletal[2,3] and cardiopulmonary systems.[4–7] Values for gross mechanical efficiency (ME) in hand-rim wheelchair propulsion hardly ever exceed 10%.[8,9] Apart from the low ME, physical work capacity in wheelchair arm work is generally very low compared to leg work and varies considerably among wheelchair users.[10–12]

As a consequence of the movement pattern and the associated strenuous (mechanical) labor,[13] hand-rim wheelchair users develop serious upper-body overload injuries, primarily in the shoulder and hand-wrist area.[2,3,14,15] Both musculoskeletal injuries and the low ME in hand-rim wheelchair propulsion are suggested to be associated with the discontinuous and somewhat complex form of arm movements in hand-rim wheelchair propulsion. To produce work on the hand rims, the hands need to couple to a thin, rotating rim that is outside the visual field and need to exert a considerable peak force along this rotating path in a very short time span (somewhere between 0.2 and 0.6 sec). This complex task is accompanied by a number of mechanical, anatomical, and physiologic constraints: (1) the discontinuous rhythm: a rather short push period and a relatively long recovery period to bring the hands to the initial position; negative dips in the force at start and end of the push phase, which essentially brake the wheels; a "non-optimal" (i.e., nontangential) force direction; during the push, the wrists are in an extended position while the fingers are strongly flexed and the wrist travels from a considerable degree of radial deviation toward excessive ulnar deviation; and muscle-based, hand-wrist, and shoulder stabilization needs to be generated to stabilize the highly flexible wrist and shoulder mechanisms and to allow energy transfer.

Simultaneously, long-term wheelchair use seems to be associated with an increased tendency for cardiovascular diseases.[16,17] This is indirectly explained by the inherent inactive lifestyle of many wheelchair users and the imbalance between physical capacity and the strain of everyday wheelchair use in this population. Short-term physical strains of wheelchair propulsion are fatigue, local muscle soreness, and discomfort of the arms, which in turn may induce inactivity (i.e., a sedentary lifestyle). Inactivity will subsequently lead to a reduction of physical capacity or fitness. Again, this will provoke an earlier onset of fatigue and discomfort, further stimulating the negative spiral of inactivity and de-conditioning.[6,18–20] In the long run, this process may lead to serious secondary health problems. Apart from that, a reduction of the freedom of mobility and range of action emerges, which may affect participation. An imbalance between stresses imposed on the biologic system, experienced physiologic strain, and physical work capacity seems basic to these notions.[21]

The natural solution to this mobility problem generally will be the provision of an electric wheelchair or the hybrid hub–motor-assisted, hand-rim wheelchair.[22,23] The latter does require a 60% lower exercise intensity than normally required in hand-rim propulsion. Clearly, an electric wheelchair will reduce exercise to a level of close to 0%, and thus stimulate the process of de-conditioning even more.

From the point of de-conditioning and the related health perspective, physical exercise in the form of self-propulsion is to be preferred whenever possible. Of course, given the initial problems of long-term hand-rim wheelchair use, propulsion conditions must be optimized as much as possible.[24–28] From an ergonomics perspective, there are basically three strategies that may help prevent long-term overuse injuries and improve comfort of wheelchair propulsion. One is the deployment of different, less stressful movement and force patterns through the ergonomic optimization of the propulsion mechanism and other aspects of the wheelchair-user interface. Another is the improvement of the capacity of arm structures through well controlled strength and endurance training activities, thus leading to a reduction of the relative strain and, possibly, absolute strain. Finally, there is the strategy of the reduction of the task load of wheeled ambulation through improved vehicle mechanics of the wheelchair.

Over the years, wheelchair athletes have been the driving force behind wheelchair ergonomics and innovation. Over the last decades, wheelchair sports have evolved into a variety of highly specialized, top-performance disciplines. High-performance wheelchair use requires the use of specifically optimized wheelchair designs and interfacing and highly trained physical and technical qualities of the athletes. Next to the athletes and coaches, experimental research has contributed to the development of the sports for those with disabilities in general[19,20,29] and to wheelchair sports in particular[30–32] in a limited but essential way. Apart from guidelines for training and physical activity in sports and daily life and rehabilitation,[18–20] highly specialized sports and task-specific wheelchair designs and materials have evolved[22,30] (For an up-to-date presentation of wheelchair models and sports-related developments, the reader is referred to recent issues of *Sports 'n Spokes.*). Through consistent biomedical experimentation and theorizing, research helps in understanding the many different mobility and exercise-related issues in rehabilitation, sports, and daily life. Biomedical research also has contributed to a better understanding of the consequences of a life in a wheelchair and the subsequent technical requirements of wheelchairs as an optimal mobility device. Biomedical research has generated an evidence base for successful wheeled-technology developments, ergonomics of design, and fitting procedures.[30–32]

The purpose of the current review is to present an evidence base for the currently booming development of alternative manual wheelchair-propulsion mechanisms—not only crank-driven wheelchairs, but also lever propelled ones—and for their possible role in the improvement of freedom of mobility and the prevention of overuse injuries.

ALTERNATIVE MODES OF PROPULSION

In the late 1960s, physiologic studies showed that other forms of

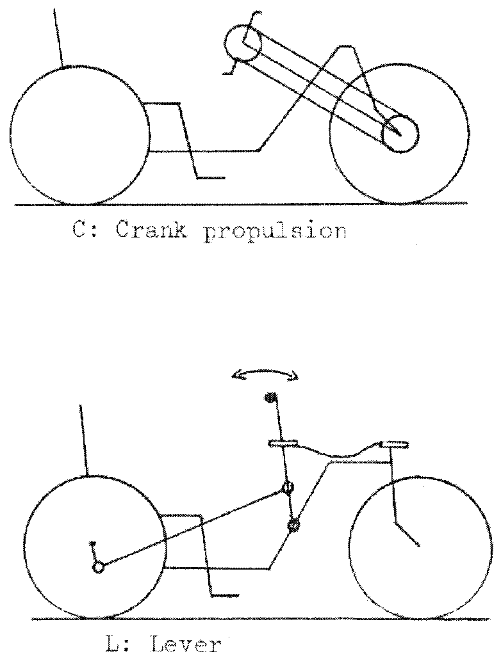

Figure 1: Examples of a fixed-frame, crank-propelled tricycle and a frequently used attach-unit, synchronic arm-crank system in The Netherlands.

Figure 2: Hubcrank use in a racing wheelchair on a motor-driven treadmill.

arm work than hand-rim use were more efficient and thus physically less straining to the cardiorespiratory system and possibly the musculoskeletal system. Using these propulsion mechanisms improves endurance time and peak performance and may prevent the occurrence of arm injuries. Crank and lever propulsion systems were the most frequently seen alternative manual wheelchair-propulsion mechanisms in the 1950s and 1960s. These mechanisms considerably reduce the physiologic strain in comparison with hand-rim propulsion,[33–36] despite typical drawbacks of size, weight, and appearance.

The subsequent economic development shifted the focus of wheeled mobility further toward electrical and mechanical propulsion mechanisms, as it did for the general population.

Not too long ago, however, more contemporary designed alternative propulsion mechanisms became commercially available again—initially as devices for training and sports and later for general use in daily life.[30,37–39] These lever and crank propulsion systems, because of their improved design and higher mechanical efficiency, allow a higher coasting speed and an increased endurance time. As a consequence, open-category sports competitions in upper-body–propelled tricycles have become popular (Again, for an up-to-date description of hand-cycle models and sports-related developments, the reader is referred to recent issues of *Sports 'n Spokes*.).

Moreover, in developing countries, arm-crank–propelled and lever-propelled wheelchairs have been preferred for obvious reasons[40,41]: large front and rear bicycle wheels, chain-and-sprocket bicycle technology, and local tubing material and welding techniques allow for a self-supporting industry. Typical examples of such crank-propelled and lever-propelled tricycles are shown in Figure 1.

In contrast to hand-rim wheelchair propulsion, crank and lever systems allow natural forms of both synchronic and asynchronic arm use, as well as one-arm use. The common use of gear systems allows wheelchair propulsion under various environmental conditions (steep slopes, rough terrain) and for different user groups. Given these practical improvements, the question of the experimental evidence base needs closer attention.

Hub Crank. A relatively unknown alternative wheelchair propulsion mechanism is the hub crank (Fig. 2), a device that allows for a continuous motion of the hands around the wheel hubs of the rear wheels of a track or racing wheelchair through the use of hub-connected cranks.[42–44] Given the low seat position in racing wheelchairs, hub cranks allow continuous force exertion onto the wheels in a more or less similar orientation of the arms and hands as seen in hand-rim propulsion with a hand rim of similar size. The hub crank has a well fitting handgrip that rotates freely around an axle perpendicular to the crank and adapts itself to the orientation of the hand as a consequence of the implemented free wheel. The hub crank was used mainly by athletes in the second half of the 1980s in wheelchair training, sports, and recreation. However, the system appeared not highly practical because steering and braking is complicated and requires considerable learning.

From a theoretical perspective, the hub crank is a highly interesting propulsion mechanism because it so closely mimics parts of the

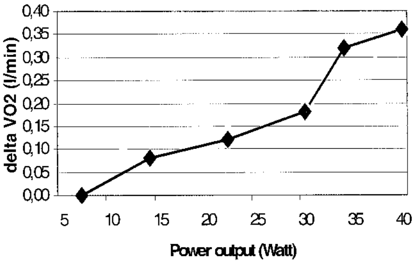

Figure 3: Oxygen cost of hand-rim propulsion minus oxygen cost of hub-crank propulsion at identical levels of power output (*delta VO2*) as a function of power output for studies of van der Vlies et al. (♦)[44] and van der Woude et al. (◇).[42]

hand-rim movement pattern. Thus, studying the hub crank may help us better understand the drawbacks of hand-rim propulsion. The efficacy of the hub crank was therefore studied in two groups of non-wheelchair users.[42,43] In van der Woude et al.,[42] the hub cranks were fitted to a racing wheelchair that was mounted on a stationary wheelchair roller ergometer. The front wheel was fixed to the ergometer frame, making steering unnecessary. In two identical submaximal exercise tests, the hub crank condition was compared with a hand rim of similar size in the same wheelchair. It turned out that the hub cranks led to a significantly lower strain. Oxygen uptake and heart rate were significantly lower at equal speed and power output. Gross mechanical efficiency was >3% higher compared with the hand-rim condition (9.1% *vs.* 12.9% on average at the heaviest condition).[42] Comparable trends were seen in a pilot study for a small group of trained wheelchair athletes who propelled their own racing wheelchair with the hub cranks and subsequently hand rims of similar size on a motor-driven treadmill.[43] Despite the limited experience of the athletes with the hub crank (and the high degree of expertise in hand-rim use), and despite problems of steering with the hub cranks on the treadmill, significantly lower strain and higher efficiencies were seen in the hub crank condition. Recently, van der Vlies et al.[44] verified these results again during hub crank and hand-rim propulsion on a computer-controlled wheelchair ergometer. Again, gross mechanical efficiency reached considerably higher values, mounting up to a difference of 4.6% (7.6% *vs.* 12.2%). A summary on the oxygen uptake for hand-rim and hub crank propulsion is given in Figure 3.

Part of the explanation for the strong benefits of hub crank propulsion is found in the expected propulsion technique. Until now, little was known of the force characteristics and coordination in hub crank propulsion. A first typical tracing of the effective force around the wheel axis during hub crank and hand-rim propulsion was presented by van der Woude et al.[42] and is shown in Figure 4. The effective force is equal to the torque around the wheel axis divided by the radius of rim or hub crank. The positive effects of the hub crank may be explained with the following notions:

The continuous circular motion in hub crank use allows both push and pull actions, thus reducing the idle periods in the cycle during which no power is generated. In hand-rim propulsion, a typical push phase is only 20% of the cycle time!

The continuous circular motion allows for contributions of both flexor and extensor muscle groups, better spreading the load of power transfer over more muscle groups than in hand-rim propulsion; this will reduce the amount of work per unit muscle mass in hub crank use.

Because of the handgrip in hub crank use, the hand and wrist have a more natural orientation to the lower arm (the handgrip adapts to the spatial hand orientation to a large extend). As a consequence, the coupling of the hand to the propulsion mechanism is suggested to be easier and less straining, with no counteracting hand moment, as is normally seen in hand-rim propulsion.[2,13] In addition, the grip force of the finger flexors might be lower, which may lead to a reduction of strain in the carpal tunnel.

In conclusion, the hub crank has

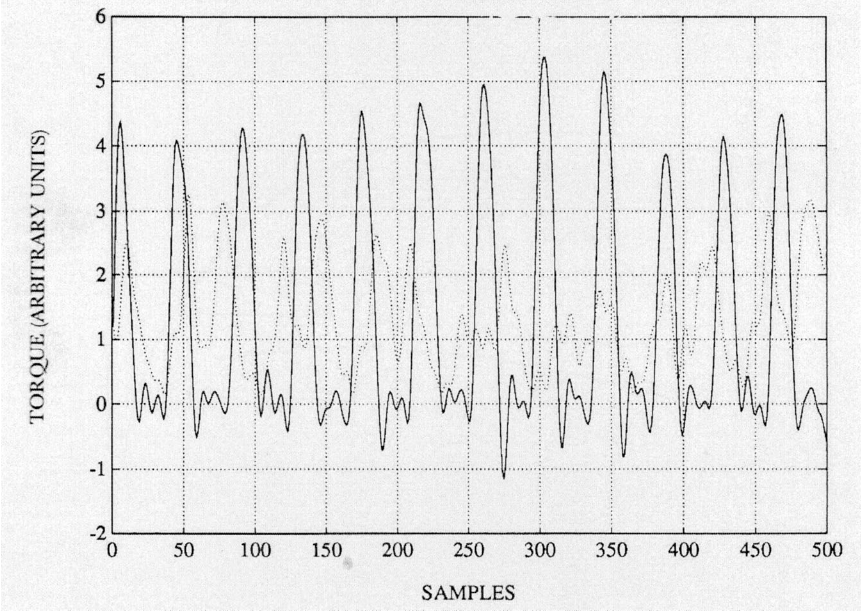

Figure 4: Torque production around the wheel axis during hub crank and hand-rim wheelchair propulsion. Torque is in arbitrary units. Adapted from van der Woude et al.[42]

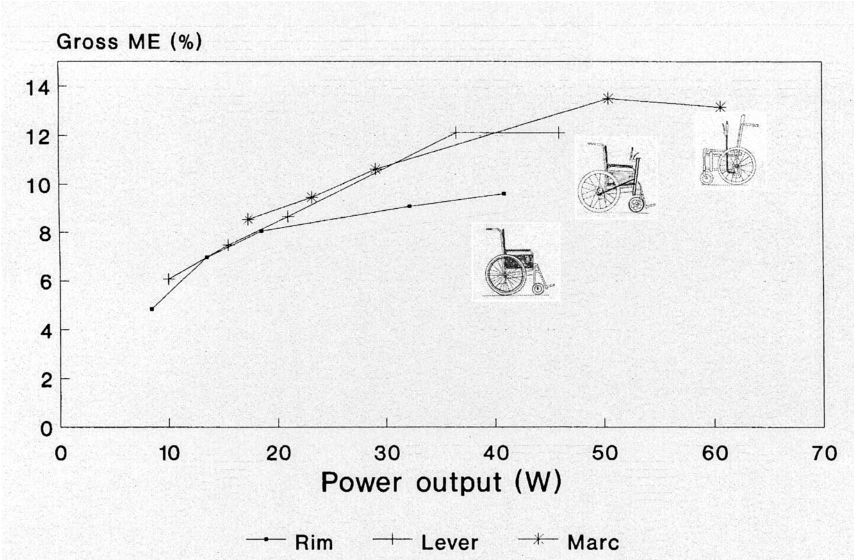

Figure 5: Mean gross mechanical efficiency (*ME*) of a group of eight male non-wheelchair users using a wheelchair with hand rims, crank-to-rod levers, and a prototype lever mechanism (Marc) at different levels of power output; adapted from van der Woude et al.[49]

clear physiologic advantages over the hand rim, and it also may prove beneficial for overuse problems in the arms. Its use to date, however, has been restricted to track wheelchairs and outdoor use. The wheelchair with hub cranks is hard to steer, braking is more complicated, and its increased width (+0.15 m) complicates indoor use. This may explain why hub cranks are not widely used. However, these usability aspects might be improved with design-oriented research and innovations.

Lever Propulsion. Since the 1960s, the German group around Hildebrandt and Engel has conducted considerable research into the physiologic benefits (and drawbacks) oflever-propelled wheelchairs.[35,45–48] In lever propulsion, the hands make a cyclic motion—either synchronic or asynchronic—in a sagittal plane ventral to the subject. Generally, force is indirectly transferred onto the wheels through a fairly simple lever mechanism in a push and/or pull phase. Lever propulsion was thought to be an appropriate alternative for outdoor wheelchair use, and even for indoor use. Especially for those individuals with limited energy resources or those with the urge to go beyond the local area around the house, lever propulsion may be an adequate alternative mobility device.

A simple and efficient commercially available lever design is the crank-to-rod system. Engel and Hildebrandt[35] and van der Woude et al.[24,49] showed that these conventional crank-to-rod lever mechanisms were more efficient and less energy consuming when compared with the conventional hand-rim wheelchair. The crank-to-rod mechanism is a mechanically very simple unilateral or bimanual lever-propulsion system. It drives the rear wheels through a crank-and-rod system fixed to the hub of the rear wheel or wheels. Power transfer of the levers is frequently combined with the steering task through the handles. Crank-to-rod systems are used in contemporary four-wheeled wheelchairs and in the tricycle. The length of the levers can generally be adjusted. Compared with hand rims, the hands are much more in a natural segmental position and spatial orientation, and they are coupled to the handgrip with limited gripping effort. Force can be exerted in a push and pull direction, thus using a larger number of muscles around the shoulder and elbow compared with hand rims. The external force direction is possibly closer to the center of the shoulder mechanism, thus reducing the torque around the joint. In general, not much research work has been done on force production compared with the cardiorespiratory system. Only effective force (perpendicular to the lever in the plane of lever motion) has been described.[25,50] Essentially, three-dimensional force tracings are required to better understand coordination and effectiveness of force production.

With respect to the conventional gripping roller-lever mechanisms, crank-to-rod systems seem superior in terms of energy cost and physical strain.[49] Absolute differences for ME up to 3% are seen. The gripping roller allows force transfer from the lever onto the wheel through a roller that grips the tire only in the push phase, a system highly sensitive to the quality of the mechanics and maintenance.

Lever propulsion is also suggested to be an appropriate alternative for one-arm wheelchair use. Little to no research has been done in this respect. Unilateral arm use is clearly more straining because of the further reduction of active muscle mass and the need for stabilization of the trunk to the asymmetric force application.[49] In that perspective, the lever design and mechanics probably play a major role. Not just the lever as such, but also the ergonomics of the interface, the mechanics of force transfer, and the vehicle mechanics of the wheelchair will eventually determine efficiency and physical strain.

In terms of energy cost and efficiency, the simple crank-to-rod lever mechanisms are hard to beat. Negligible energy is lost in the transfer of energy from the hand to the wheels. Newly designed daily use lever mechanisms, such as the Capstan[51–54] and the Marc,[49] were developed to overcome the drawbacks of the crank-to-rod levers: no free wheel, no reverse, and the sinusoidal force characteristic of the lever. Both systems have shown to be almost equally efficient and, to some extent, even more functional (also with the opportunity to implement a reverse, an internal brake, and even a gearing system) than the crank-to-rod mechanism. This is demonstrated for the Marc in Figure 5. Lever-propulsion mechanisms have been primarily developed for daily use and for indoor use.[55] Maneuverability and steering in small spaces remains more problematic using levers, even for the new prototypes.

Important advantages of the lever-propelled wheelchairs and tricycles are the straightforward and continuous upper-arm movement pattern with involvement of a much larger muscle mass (flexion *and* extension) during the full circular work cycle. This spreads physical strain over a larger number of muscles. It is also hypothesized that somewhat larger muscles (latissimus dorsi, pectoralis, and trapezius muscles) are more continuously involved. Forces may also be applied closer to the preferred range of motion and directions of the human system compared with hand-rim propulsion. No (peak) impact forces in joints and muscles seem to occur because of the continuous coupling of the hand to the propulsion mechanism and the almost continuous and more constant force application. The spatial orientation of the hand and wrist is within the visual field of the user, which seems to improve motor control. Moreover, as in hub crank use, lever propulsion allows a much more relaxed coupling of the hand and a fully neutral orientation of the wrist. This will considerably reduce the need for stabilizing muscle activity. The latter seems so prominent in hand-rim wheelchair propulsion.[2,13,56]

Further ergonomic improvement of these systems seems feasible. With respect to levers, the mechanism of force transfer onto the wheels needs careful attention. In the crank-to-rod mechanism, force transfer is simply produced through a series of levers and cranks with a fixed range of motion. The force transferred to the wheel is sinusoidal with zero force when the levers reach the end phases of the linkages. Apart from the absence of a freewheel and gears and the fixed range of motion in the push and pull phase—which demands are easily met in bracket-chain–related lever systems[57]—the crank-to-rod lever mechanism is efficient. Also, the prototypes described by Engel and Seeliger,[52] Seeliger,[53] and van der Woude et al.[49] fulfill these requirements.

The use of the currently available high-number gear boxes that are based on bicycle technology, which can easily be built into a lever system, may improve individual performance even further. A significantly decreased strain and higher ME (1.5–2% absolute increase in ME) with heavier gears during asynchronic tricycle lever propulsion in a group of non-wheelchair users has been found by van der Woude et al.[57] Results seem to indicate the opportunity of further ergonomic optimization of the wheelchair-user interface in terms of mechanical advantage and shoulder-to-seat orientation. Lever length, handgrip, and spatial orientation, as well as the seat orientation, seem to be other issues for optimization.[49] Whether synchronous or asynchronous lever use is preferable is still under debate. Glaser et al.[58] demonstrated beneficial effects of asynchronic arm motions during hand-rim propulsion. Engel et al.[45] and van der Woude et al.[49] compared synchronic and asynchronic lever propulsion but did not find significant differences. In contrast, Oertel et al.[51] showed significantly lower levels of strain for synchronic lever use.

Lever-based tricycle sports or recreational wheelchairs[37,57,59] are a proper alternative for outdoor wheelchair use. These, as well as lever-based systems for developing countries, have become commercially available.[24] Today, tricycle use is, however, strongly dominated by crank-propelled systems.

Arm-Crank Propulsion. During the last few decades, arm-crank exercise has received considerable attention because of its role in exercise testing of the upper body.[10,60–62] Experimental results indicate that stationary arm-crank ergometry is far more efficient than hand-rim propulsion and that peak power output is considerably higher. At equal power output, physical strain and cardiac output are significantly lower[34,36,60–68] than in hand-rim wheelchair propulsion. In accordance with Sedlock et al.[65] and Tropp et al.,[68] Martel et al.[36] found a significantly higher gross mechanical efficiency for arm-crank exercise compared with hand-rim wheelchair exercise in 20 subjects with paraplegia (peak ME values, 16.3% *vs.* 11.6%; see Fig. 6). According to Glaser et al.,[58] Martel et al.,[36] McConnell et al.,[64] and Sedlock et al.,[65] peak power output in maximum arm-crank ergometry is substantially higher compared with wheelchair ergometry, but results on peak cardiopulmonary parameters are contradictory. According to Martel et al.,[36] peak power output was on average 97 ± 25 W in arm-crank exercise *vs.* 74 ± 19 W in wheelchair ergometry. Glaser et al.[58] presented similar mean figures for a mixed group of wheelchair users and able-bodied individuals: respectively 93 W and 59 W.

The above results, however, are limited to arm-crank ergometer exercise. Tricycle wheelchair arm-crank exercise (hand cycling) has received much less systematic research attention, despite the fact that the crank-

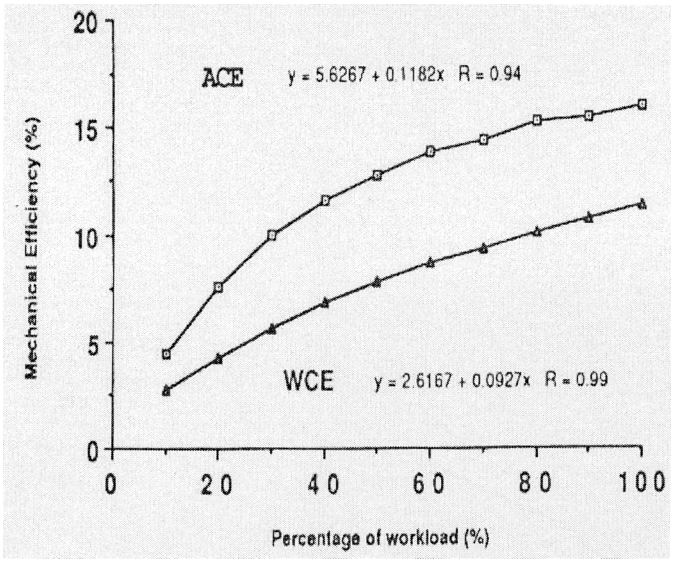

Figure 6: Mean gross mechanical efficiency during hand-rim wheelchair propulsion (*WCE*) and arm-crank exercise (*ACE*) at relative levels of power output; adapted from Martel et al.[36]

propelled wheelchair devices have become extremely popular today. The limited number of experimental studies that dealt with hand cycling showed that, in general, wheelchair crank propulsion is considerably less straining than hand-rim propulsion at submaximal effort (Fig. 7).[24,35,69] Oertel et al.[69] evaluated a hand bike with a lever mechanism (Capstan) and hand-rim wheelchair propulsion on a wheelchair track. Energy cost and heart rate were significantly lower for the hand cycle (Speedy-bike), whereas endurance time and coasting velocity were increased.

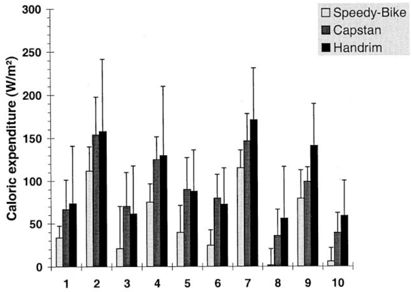

Figure 7: Mean (and standard deviation) energy cost during different parts of a wheelchair track using a hand rim, lever, (Capstan) and hand bike (Speedy-bike); from Oertel et al.[69]

Again, the overall more effective and continuous use of a larger number of arm and trunk muscles, as in lever and hub crank propulsion, seems crucial to this notion. Because of the orientation of the arms in space and of the backrest, and because of the continuous movement pattern, individual shoulder muscles will be less strained in hand cycling. Also, the spatial orientation of the external hand forces seems more closely related to the shoulder mechanism. Again, the gripping action of the hands is more natural and probably far less straining. Important to note here is the absence of theory-driven research that helps clarify the mechanisms behind the important differences among the different wheelchair propulsion mechanisms.

The possible use of large numbers of gears and the use of different cranking modes (synchronic vs. asynchronic) are also strong benefits of hand cycles. Both the effects of gear ratio and mode of exercise were recently studied by van der Woude et al.[70,71] Results of a group of 12 male non-wheelchair users showed significant effects on oxygen uptake, ventilation, mechanical efficiency, and heart rate for both gear ratio and mode of exercise. Overall, the light gear ratio showed a higher efficiency in comparison with the medium and heavy gear use. Fink[47] found crank propulsion with a 1:0.73 gear ratio to be more efficient and less strenuous than the 1:1 gear ratio. The detrimental effects with a heavier gear setting in van der Woude et al.[70,71] are in contrast with synchronous or asynchronous arm work of different studies (arm crank ergometry,[72,73] hand-rim wheelchair propulsion,[9,56] and lever wheelchair propulsion[57]). These studies found higher efficiencies with a higher mechanical advantage or heavier gear setting. This may, however, be explained with the difference in average arm-hand speed or movement frequency in the presented experiments and thus with differences in the evaluated range of mechanical advantage in relation to the average coasting speed. Coasting speed was very low in van der Woude et al.[71] Low to very low values for revolutions per minute (rpm) were the consequence (lowest, 24 rpm; highest, 44 rpm) compared to Romkes et al.[72] (50 and 70 rpm), Hardison et al.[74] (50–80 rpm), and Powers et al.[73] (50–90 rpm). With a constant power output, the heart rate and oxygen uptake plotted against the crank rate is expected to form a U-curve, as is more or less described by Hardison et al.[74] and Powers et al.[73] Simultaneously, for gross mechanical efficiency a hill-shaped curve is expected to be found, indicating that there is a most economical crank rate at a given power output. This can be exemplified if one combines findings of Powers et al.[73] and van der Woude et al.[71] In Powers et al.,[73] at a mean power output of 45 W, efficiency dropped from 15% to 13% when crank rate went up from 50 to 90 rpm. In the current study, at a mean power output of 47.5 W and rate of 24, 36, and 44 rpm, respectively, efficiency was 10.9, 11.9, and 12.2%, respectively. As a consequence, this will have an impact on the position in the force-velocity relationship of the various muscles involved in this task. With a heavier gear, the force to be exerted will increase whereas the velocity of the movements (and muscle contraction) drops. This may impact local blood flow and may lead to a reduced oxygen supply and production of an increased level of metabolic byproducts. Also, the need for increased finger-flexor and hand-flexor activity to secure the grip on the handle through the 360-degree circular action in the heavier gear setting may have influenced energy cost in comparison to the light gear setting.

The synchronic tricycle arm cranking was shown by van der Woude et al.[70,71] to be more efficient and less straining than asynchronic arm movement. This held for all gear settings evaluated. This notion was also substantiated for a population with lower limb amputations on a stationary arm ergometer.[75] This seems to coincide with the general preference for a synchronic crank setting as is seen in sports practice, but it is in contrast with findings of Hopman et al.[67] and Mossberg et al.[76] The latter difference may be associated with the different effects of stationary arm-crank–ergometer exercise and hand cycling.

In hand cycling, the arms and hands combine power transfer with steering. The asynchronic mode will probably lead to a less stable crank set and to a less straight coasting line. This implies an inherent longer distance to be traveled. Moreover, in asynchronic hand-cycling power transfer is accompanied by a need for stabilization of the crank set through co-contractions of upper-body musculature. In the asynchronic arm mode, there is also a need for stabilizing muscle activity of the trunk in response to the rotating effects of external forces at the hands on the longitudinal axis of the trunk. This partly explains the expressed preference for synchronic crank use in daily life hand cycling. The supporting role of the backrest onto trunk and the consequently more stable trunk position, especially relevant in those with limited trunk control, may be an additional explaining factor. The backrest itself serves as a stable medium to generate reaction forces. Moreover, the beneficial effects of the synchronic arm mode may also be caused by the larger effective muscle mass of the trunk, which allows the weight of the trunk to be effectively used in propulsion. In the event of proper trunk control, trunk flexors and extensors will actively contribute to power production.

Apart from gear ratio and mode, different crank interface aspects may be subject to optimization. Various studies investigated the effects of crank-axle height, crank length, and cranking rate in stationary arm-crank ergometry.[72,77,78] With the exclusion of crank rate, no univocal indications of optimum geometry characteristics could be derived. Romkes et al.[72] did not find any effect of the spatial crank orientation either horizontal to the shoulder or positioned above shoulder height. The role of a chest restraint appeared to be negligible in the 13 healthy male subjects they studied.

A recent analysis of Janssen et al.[79] showed the high performance (in time and power output) of subjects with lower-limb disabilities and subjects with tetraplegia during a 10-km race and during a maximum hand-cycling exercise test on a motor-driven treadmill. However, ME was lower than anticipated. To what extent individual functionality has an impact on synchronic or asynchronic arm use, gear setting, or any other design characteristic requires further study.

The overall beneficial characteristics of hand cycle, lever, and hub crank propulsion mechanisms are summarized in Table 1. These alternative modes of propulsion clearly need further ergonomic optimization with respect to the wheelchair-user interface (gear ratio, lever or crank length, grips or handle bars and their spatial orientation, and seat orientation and angulation), but overall, they are to be preferred over hand-rim wheelchairs for outdoor manual-wheelchair use (not only in sports conditions).

The increasing and widespread practical use of hand cycles[79] and attach-unit crank systems (fifth-wheel coupling mechanisms; Fig. 8), especially among those who are generally viewed to have too limited resources for outdoor manual wheelchair use, stresses the practical relevance of arm-crank propulsion mechanisms for large groups of wheelchair users. It further stresses the need for research into subject-related questions of stress, strain, and work capacity and their associations.[21] Furthermore, it emphasizes the importance of understanding possible options for further ergonomic optimization of the wheelchair-user system with respect to both the cardiorespiratory and musculoskeletal systems.

PROPULSION TECHNIQUE AND MECHANICAL STRAIN

It is expected that wheelchair users will benefit in more than just a physiologic sense from alternative modes of wheelchair propulsion. Mechanical loading of the muscles and joints is suggested to be lower in crank and lever use. However, in contrast to hand-rim propulsion, little to no research has been conducted in this realm. DeCoster et al.[80] studied muscle activation patterns during hand cycling, and Brubaker[81] conducted a similar study in lever propulsion. Bennedik et al.[48] theoretically described force production in lever, hand-rim, and crank propulsion, but performed no measurements. Lesser[25] and Engel et al.[50] evaluated effective forces in lever propulsion. Lower peak force during hub crank propulsion *vs.* hand-rim propulsion over a series of cycles (Fig.

TABLE 1
Characteristics of different propulsion mechanisms, partly based on experimental data

	Hand Rim		Hand Cycle			
	Basket	Racing	Fixed	Attach Unit	Lever	Hub
Max ME (%)	<10	<8	>13	>13	>13	>12
Strain CVS	High	High	Low	Low	Low	Low?
Strain MSS	High	High	Low	Low	Low	Low?
Risk RSI	High	High	Low?	Low?	Low?	Low?
Top speed (km · hr^{-1})	15	30	>30	30	30	30
Mass (kg)	<10	<8	10–15	15	10–15	<10
Coupling hand	−	−	++	++	++	+
Force direction	−	−	+	+	++	+
Bimodal	−	+	+	+	+	+
Continuous work production	−	+	+	+	+	+
Outdoor use	+	++	+++	+++	++	+
Maneuverability	++	±	−	−	−	−
Indoor use	++	±	−	±	−	−
Steering	++	±	±	±	±	−
Brake	±	−	+	+	+	−
Transportation	++	++	−	+	−	±
Maintenance	+	+	±	±	±	+

CVS, cardiovascular system; MMS, musculoskeletal system; RSI, repetitive strain injury.

2) was shown by van der Woude et al.[42] Hight and Zomlefer[77] was the only

Figure 8: Typical examples of tricycles with asynchronic (one gear) arm-crank propulsion and synchronic crank-to-rod lever propulsion as were used in the experiments of van der Woude et al.[24] The tricycles were developed for use in underdeveloped countries.

study to produce some information on force production in hand cycling. Neither of these studies served any conclusive information because studies were on effective external force only or lacked comparisons with hand-rim force production. Given the expected force characteristics and muscle loading of crank propulsion, it is suggested that more frequent hand cycling (in stead of hand rims) may reduce the commonly seen tendency for overuse injuries in athletes and wheelchair users in general.[2,3,14,15] Upper-body overuse injuries are a serious risk for secondary disability in users of hand-rim wheelchairs. Mechanical loading of the arms during hand-rim propulsion is an object of important research efforts today.[2,13,56,82–84] For this purpose, highly specialized measuring systems have been developed. In conjunction, complex biomechanical modeling is required to shed light on the mechanisms of loading on the specific internal structures that are most vulnerable.[13,56,82–84] The limited results available seem to explain at least part of the possible mechanisms of overuse injuries of the upper limb musculoskeletal system in hand-rim wheelchair use.[2,13,82] Research also indicates the tendency of the biologic system to seek for the optimum task load within the boundary conditions set forward in the task.[13,56,84] Given the suggested beneficial characteristics of crank and lever propulsion, there is a strong need for detailed measurement technology for further research into the mechanical load, coordination, and gross mechanical efficiency during hand cycling and lever wheelchair propulsion.

PERFORMANCE CAPACITY

Considerable information is available on the physical work capacity of the population of wheelchair users. Physical capacity is indeed highly variable among wheelchair users, depending on age, functionality, type of injury, and training status.[10,11,12,58,61,63,85,86] What has become evident, however, is the strong difference between peak power production (as well as physical strain at equal submaximal power output) using hand-rim propulsion mechanisms *vs.* crank or lever propulsion mechanisms. This should be kept in mind when comparing different studies.

What is also clear from the literature is that people who use wheelchairs can be trained and can improve their performance capacity over time, during[85] or after rehabilitation,[86] and thus can reduce the experienced strain of daily activities[87,88] and probably make those activities less fatiguing, braking the negative inactivity spiral. Being physically active during daily life by choosing a hand-propelled wheelchair instead of a motor driven wheelchair and using a hand cycle outdoors instead of a hand-rim–propelled wheelchair is suggested to help in improving physical work capacity[18–20] and preventing the negative inactivity cycle. Sports activities are especially helpful in stimulating physical fitness.[18–20,86,88] Whether a physically active lifestyle can help prevent the overuse injuries of the upper limbs remains to be seen. Recent results of Curtis et al.[3] do indeed suggest such a phenomenon. Further research in that realm is clearly required.

PHYSICAL STRAIN

Each activity in life leads to a measurable physiologic response,[89] the physical strain of that activity. Physical strain of activities of daily life are high in hand-rim wheelchair use.[6,7] Reduction of the physical strain of wheelchair propulsion has been the central focus of this study. The ultimate reduction of wheelchair-related physical strain is obtained when fully abstaining from the manually propelled wheelchair. This can be a proper solution for individual or environmental reasons, but this is always at the cost of reducing physical strain to little more than zero. The biologic system will adapt to that level of de-conditioning.

When manual wheelchair propulsion is the means of mobility of choice, the physical strain must be minimized to eventually ensure maximum freedom of mobility. This review dealt with the optimizing of the wheelchair-user interface in terms of different propulsion mechanisms. Within each propulsion mechanism, interfacing must be optimized, as has been stressed for hand-rim–propelled wheelchairs by various research groups during the past three decades.[24–27,30,90] Changing the propulsion mechanism to crank or lever is a very fruitful change in terms of physical strain for certain activities of daily living. Moreover, improving work capacity will reduce the relative physical strain. A final way of reducing the physical strain in manual wheelchair use is the reduction of the physical stresses that act on the wheelchair-user combination from a purely mechanical perspective. Through the improvement of the vehicle mechanics of the wheelchair—typical wheelchair and environmental characteristics (Table 2) that are associated with internal and rolling resistance and air friction—the physical strain of wheelchair use can further be reduced. The mechanics of the wheelchair obeys simple laws of physics and optimization is rather straightforward. It will reduce the opposing forces during wheeling[91–93] and thus minimize physical strain.

TABLE 2
Mechanical factors and the way in which they influence rolling resistance

Factors	Rolling Resistance
Body mass ↑	↑
Wheelchair mass ↑	↑
Tire pressure ↓	↑
Wheel size ↑	↓
Hardness floor ↓	↑
Camber angle ↑	?
Toe-in/out ↑	↑ ↑
Castor shimmy ↑	↑
For-aft position center of mass closer to large rear wheels	↓
Folding frame (*vs.* box frame)	↑
Maintenance ↓	↑

CONCLUSION

It may be concluded that crank-propelled and lever-propelled wheelchairs allow the majority of wheelchair-dependent individuals to be more mobile outdoors, have a larger power output, and have a larger endurance time or velocity. This allows them to travel for longer distances or at higher speeds. Even those with severe upper-body impairment, such as those with cervical spinal lesions, seem to benefit from these propulsion mechanisms. Using manually propelled wheelchairs under optimum conditions will stimulate physical activity and may therefore help prevent further de-conditioning that is so closely linked with life in a wheelchair.

To date, only very limited research information is available on the physiology and biomechanics of rigid-frame and attach-unit lever-propelled and crank-propelled wheelchairs in sports and daily life. The possibilities of ergonomic optimization of the design and geometry of the wheelchair-user interface in different groups of users have not been dealt with. Moreover, the suggestion that crank and lever propulsion are far less demanding for the musculoskeletal system is purely circumstantial. Little is known of the mechanical stress during upper-body work and of its relationship with ME and energy cost. There is a need for systematic study of crank and lever use from a combined biomechanical and physiologic perspective among different groups of individuals, both non-wheelchair and wheelchair users (with varying levels of ability and functionality), to ensure a proper evidence base for wheelchair design and fitting and for training and exercise guidelines.

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