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*A Review Article*

# Wheelchair racing sports science: A review

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**Abstract**—Wheelchair racing science and the performance of athletes involved in wheelchair racing have developed rapidly in recent years. With increasing interest in this sport, the need arises to identify areas where further research is necessary and cooperation between individuals with various backgrounds is encouraged. Many of the problems facing investigators in this field require knowledge in several areas of science and engineering, which suggests an interdisciplinary approach to these issues. Further progress would also benefit from the development of more quantitative methods for the classification of wheelchair athletes, or a restructuring of the classification system; development of sophisticated instrumentation for racing wheelchairs; standardization of test procedures and more complete reporting of results of studies; and, more in-depth mathematical modeling and computer simulation of wheelchair racing. This review presents an overview of four areas of wheelchair racing science: 1) classification of wheelchair athletes; 2) design and analysis of racing wheelchairs; 3) biomechanics of racing wheelchair propulsion; and, 4) training and coaching of wheelchair racers.

**Key words:** *athletic training, biomechanics, classification of wheelchair athletes, instrumentation, racing wheelchair, sports psychology.*

## INTRODUCTION

There are no statistics kept on the number of participants involved in wheelchair sports. However, racing wheelchair manufacturers estimate that over the last 5 years more than 10,000 racing wheelchairs have been manufactured worldwide, with the majority being produced in Europe, Japan, and North America. The number of participants in wheelchair sports, especially wheelchair racing, is growing rapidly, as is apparent in the number of wheelchair racing participants competing in major road races (53).

The growing number of competitors and the increasing quality of the competition have fostered interest in wheelchair sports science, with wheelchair racing and basketball leading the field (10). **Figure 1** is a typical example of wheelchair racing.

There are numerous studies of persons with spinal cord injuries as applied to sports and exercise (25,26). This review represents a significant portion of the work published in the field of wheelchair racing science.

## HISTORY AND DEVELOPMENT OF WHEELCHAIR RACING

Shortly after World War II, Sir Ludwig Guttman and his colleagues originated wheelchair sports as a rehabilitation tool at Stoke Mandeville Hospital in England (63). This developed out of the need to provide exercise and recreational outlets for the large number of young persons recently injured in the war. News of Dr. Guttman's success with the rehabilitation of his patients through the use of sports soon spread throughout Europe and to the United States. In 1948, he organized "Games" for disabled British veterans. In 1952, the Games developed into the first international wheelchair sporting competition for the

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**Figure 1.**
An example of wheelchair racing. (The final of the Class V 1500-meter at the 8th Paralympic Games.)

disabled, with participants from the Netherlands, the Federal Republic of Germany, Sweden, and Norway. During this event, the International Stoke Mandeville Games Federation (ISMGF) was formed to govern and develop wheelchair sporting competitions; an organization that continues to be the international governing body for wheelchair sports. The ISMGF established ties to the International Olympic Committee (IOC), thus expanding the scope of wheelchair sports.

The first international games for the disabled held in conjunction with the Olympic Games took place in 1960 in Rome, Italy. The name "Paralympics" was coined during the 1964 Tokyo games and, as such, subsequently held every four years.

In the early years of wheelchair racing, participants used bulky standard wheelchairs and did not compete in events with distances over 200 meters. In the 1970s, athletes started to modify their wheelchairs for specific sports and began to take an interest in road racing.

In 1975, a young paraplegic became the first person to compete in the Boston Athletic Association Marathon in a wheelchair. This opened the door for many future wheelchair road racers, prompting Dr. Caibre McCann, a leading physician for the ISMGF international governing body for wheelchair sports, to say: "Running is natural, but propelling yourself in a wheelchair is an unnatural phenomenon. People never realize what a wheelchair athlete is capable of. This is a breakthrough in man's limits."[1] Within a few years, several nationally recognized road races initiated wheelchair divisions and more disabled persons began to train for these races than had ever been anticipated. In 1976, the ISMGF started to coordinate with other international sports organizations to launch a unified international disabled sports movement (46,50).

Racing wheelchairs began to evolve as special-purpose pieces of equipment easily distinguishable from everyday wheelchairs. Distances on the track were extended to include races up to 1500 meters, and during this transition, the mile record was dropped to below 5 minutes.

The early 1980s saw the development of more sophisticated racing wheelchairs and training techniques. By 1985, most racing wheelchairs no longer had any components in common with everyday wheelchairs (which had also improved dramatically), and George Murray became the first wheelchair racer to break the 4-minute mile. In the years that followed, wheelchair racing continued to progress with improved equipment, training, and nutrition; consequently, world records were continuously being broken. Wheelchair racing began the path toward recognition as a legitimate Olympic sport in 1984 when the men's 1500 meter and the women's 800 meter wheelchair races were included as demonstration events in the Olympic Games held in Los Angeles, CA.

In 1988, the 8th Seoul Paralympics were held with over 60 countries represented by approximately 4,000 athletes—the largest games to date. In addition, the 24th Olympiad included the men's 1500 meter and women's 800 meter wheelchair races as demonstration events. The record books were rewritten and many technical advances were apparent.

## THE WHEELCHAIR ATHLETE

The two major components of wheelchair racing are the chair and the athlete. This section will give a brief description of the literature available on wheelchair athletes. The number of subjects used in studies of these athletes is quite small: the maximum sample size for metabolic data is 15, most are less than ten. The subjects are generally grouped by their level of impairment due to disability (quadriplegia and paraplegia). Practically all work in the available literature has concentrated on males; qualified female subjects are apparently difficult to find.

### Physiological testing

**Table 1** shows the metabolic results for several studies of wheelchair athletes (24,28,52). There is a fair amount of variation between the studies, as might be expected for the small sample sizes. The average paraplegic values for all of the studies are 185.3 bpm and 2.14 l/min which are similar in magnitude to able-bodied subjects doing upper body exercise. However, the values for the quadriplegic subjects are noticeably lower (121.5 bpm and 0.74 l/min); this is because they do not have the functional muscle mass to elicit a higher response and their central and autonomic nervous systems are modified to a greater extent.

Only two studies of postexercise blood lactate levels are available. Pitetti, Snell, and Stray-Gundersen (59) found the 3-minute post-maximal exercise blood lactate levels to be 8.1 ± 0.7 mmol/l, while Pohlman, Gayle, Davis, and Glaser (60) found the difference between pre- and post-maximal exercise blood lactate levels to be between 2.3 and 2.6 mmol/l. No report was made on the time samples were taken.

**Table 1.**
Metabolic data for wheelchair athletes.

| Source | Max heart rate (beats/min) | $VO_2$ max (l/min) |
|---|---|---|
| | **Paraplegics** | |
| Davis & Shepard (1988) (n=15) | 181.7 ±9 | 2.24±0.14 |
| Pitetti, Snell, & Gundersen (1987) (n=8) | 180 ±2 | 1.90±0.1 |
| Lakomy, Cambell, & Williams (1987) (n=10) | 193 ±15 | 1.95±0.38 |
| Coutts & Stogryn (1987) (n=4) | 190.25±9.65 | 2.74±0.78 |
| | **Quadriplegics** | |
| Figoni, Boileau, Massey & Larsen (1988) (n=11) | 122 ±8 | 0.66±0.07 |
| Lakomy, Cambell, & Williams (1987) (n=2) | 119 ±8.5 | 1.15±0.07 |

**Table 2.**
1988 NWAA national track records.

| Meters | Men | | Women | |
|---|---|---|---|---|
| | Time in seconds | | | |
| | Quad | Para | Quad | Para |
| 100 | 20.1 | 16.8 | 23.1 | 17.7 |
| 200 | 40.1 | 32.2 | 54.4 | 35.4 |
| 400 | 79.1 | 57.5 | 90.1 | 67.9 |
| 800 | 164.8 | 120.4 | 184.4 | 138.1 |
| 1500 | 308.9 | 225.8 | 356.0 | 270.9 |
| 3000 | 689.1 | N/A | **** | N/A |
| 5000 | **** | 777.3 | **** | 902.2 |

### Track records

**Table 2** lists the 1988 National Wheelchair Athletic Association (NWAA) records for track racing (condensed to open quadriplegic and paraplegic divisions for men and women). As expected, the records for the quadriplegics are slower than those of the paraplegics. The same is true of women as compared to men.

**Figure 2** presents a plot of average speed for each national record against distance (time/distance versus distance). The maximum average speed for all of the divisions occurs in the 400-meter race; perhaps a result of the longer time needed to reach maximum speed.

Although no official national records (national bests) are kept for road racing, **Table 3** shows the analysis of 200 wheelchair road racing results. As expected, the marathon speeds are slower than the 10,000-meter speeds; however, both speeds are much greater than those of runners. In addition, elite wheelchair athletes are capable of attaining peak speeds in excess of 8.5 meters per second (19 mph) on level ground, and 17.9 meters per second (40 mph) on downgrades.

### Studies needed

Much has been done in this area, but the work is often unrelated and difficult to apply to wheelchair racing. Studies need to be performed using a number of different protocols (i.e., increasing speed, increasing resistance, increasing speed and resistance) on different devices (i.e.,

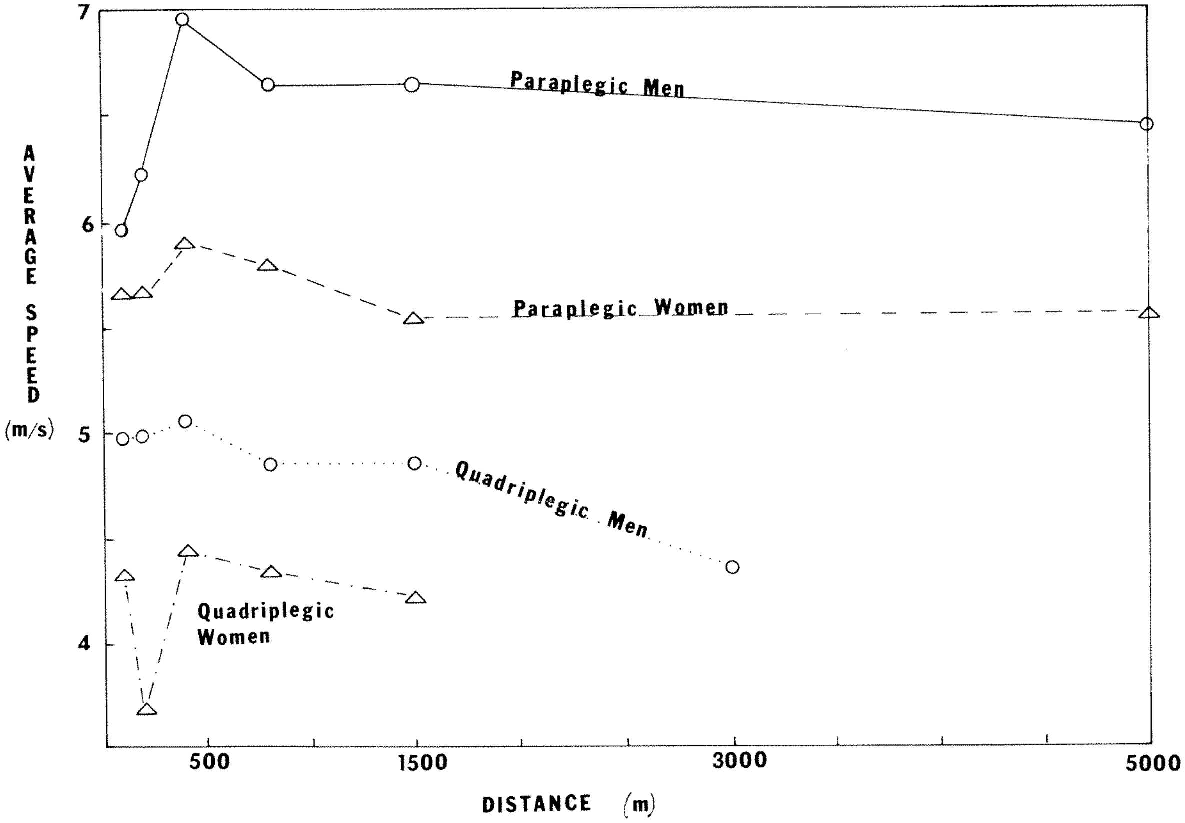

**Figure 2.**
Plot of average speed versus distance based upon the 1988 National Wheelchair Athletic Association (NWAA) records.

wheelchair ergometers, arm-crank ergometers, and treadmills). From these tests, we may be able to relate the results of different investigators to our own work. More emphasis should be placed on testing actual wheelchair users whenever possible. Studies need to be performed during actual or simulated race and training situations, so that we can relate laboratory results to practice. Relationships need to be developed to relate metabolic, cardiorespiratory, and anthropometric values to training and racing. The biodynamics of interacting with other competitors needs to be studied (e.g., the energy savings while drafting). New portable instruments need to be developed to simplify the collection and recording of mechanical, metabolic, and cardiorespiratory data during actual training and competition.

**Table 3.**
Long distance road racing results.

| | First 10 to finish | | | First to finish | | |
|---|---|---|---|---|---|---|
| | **Marathon** | **10,000m** | **400m** | **Marathon** | **10,000m** | **400m** |
| Time (s) | 7340.5 ± 605.8 | 1576.4 ± 103.1 | 57.5* | 6663.1 ± 312.5 | 1501.1 ± 66.2 | *** |
| Speed (m/s) | 5.83 ± 0.46<br>(13.0 mph) | 6.37 ± 0.41<br>(14.2 mph) | 6.96<br>(15.6 mph) | *** | *** | *** |
| Shortest time (s) | 6205 | 1380 | | *** | *** | *** |
| FAS** (m/s) | 6.85<br>(15.3 mph) | 7.25<br>(15.2 mph) | | *** | *** | *** |

*National record
**Fastest average speed

**Table 4.**
Common characteristics of wheelchairs.

| | Racing | | Standard | |
|---|---|---|---|---|
| | Meters | Inches | Meters | Inches |
| Front wheel | 0.36-0.46 | 14-18 | 0.13-0.20 | 5.1-7.9 |
| Rear wheel | 0.61-0.69 | 24-27 | 0.56-0.66 | 22.0-30.0 |
| Push-ring | 0.25-0.46 | 12-18 | 0.46-0.56 | 18.1-22.0 |
| Push-ring tubing | 0.0095-0.0300 | 3/8-1.2 | 0.0159-0.0381 | 3/5-1.5 |
| Overall length | 1.20-1.50 | 47.25-59.1 | 0.91-1.14 | 35.8-44.9 |
| Wheelbase | 0.60-1.05 | 23.5-41.3 | 0.36-0.61 | 14.2-24.0 |
| | **Kilograms** | **Pounds** | **Kilograms** | **Pounds** |
| Frame weight | 1.35-3.2 | 3-7 | 2.7-10.0 | 6.0-22.1 |
| Chair weight | 4.5-7.3 | 10-16 | 6.5-18.0 | 14.3-39.7 |

## DESIGN AND ANALYSIS OF RACING WHEELCHAIRS

Little has been reported about racing wheelchairs in the technical and scientific literature. These chairs are specialized sole-purpose pieces of equipment with distinguishing features (i.e., tubular tires, lightweight rims, precision hubs, larger wheels, and smaller push-rings, etc.) designed to optimize an individual's racing ability. **Table 4** presents an overview of some of the common characteristics of racing wheelchairs. **Figure 3** shows a drawing of a racing wheelchair with the major parts labeled.

At this time, the tools of engineering and mathematics have been applied to a very limited degree (11,12,48). The use of sophisticated analyses available from signal processing, system identification, and control theory, when used in conjunction with the knowledge to be gained from physiological, medical, biomechanical, and psychological tools, will increase the present understanding of the effects of wheelchair propulsion; specifically, the effect of wheelchair racing on the mobility-impaired individual.

Two recent papers (15,19) describe the features of racing wheelchairs in detail. With the present state of wheelchair racing, describing such a chair is like hitting a rapidly

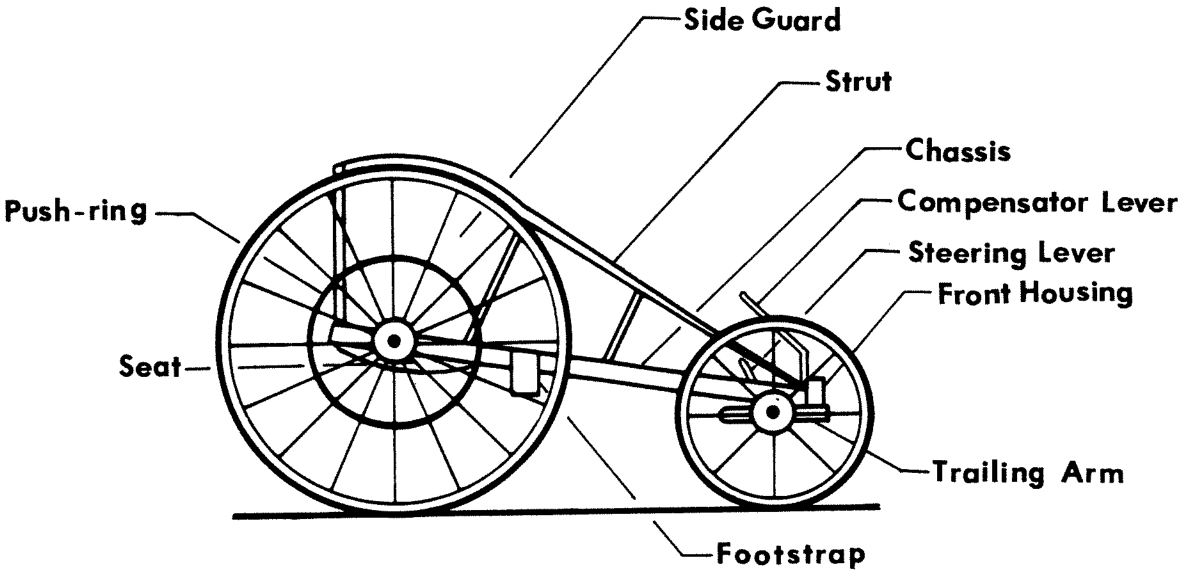

**Figure 3.**
A typical racing wheelchair.

**Figure 4a.**
Side view of an athlete in a racing wheelchair.

moving target. For example, two years ago, three-wheeled racing wheelchairs were an uncommon sight; today they represent a significant portion of the racing wheelchair market. **Figures 4a** and **4b** show an athlete in a typical racing wheelchair, and the relationship between the two. Notice the tight fit of the chair to the athlete's body.

Many factors affect the efficiency of racing wheelchairs: weight and balance; frame and wheel stiffness; rolling, bearing, and air resistance; and the frame geometry. Most of these factors have not been studied as they relate to racing wheelchairs, and none has been completely defined.

Free body diagrams for the motion of a racing wheelchair on flat ground (no road crown or road irregularities) and on an inertial dynamometer are given in **Figures 5a** and **5b**. The necessary conditions for equivalence of the corresponding differential equations for the motion have been derived by Cooper (17). Various dynamometers have been described in the literature (29,70). These dynamometers are based upon the use of electric motors for dynamic loading. The California State University at Sacramento has, perhaps, the most sophisticated wheelchair dynamometer: it is computer-controlled and capable of simulating a number of different course scenarios and control algorithms (17). Their dynamometer simultaneously measures and controls wheel torque, speed, and power. They are presently working on controlling heart rate and developing some interactive video games.

**Figure 4b.**
Front view of an athlete in a racing wheelchair.

York and Kimura (78), as well as Higgs (42), have conducted investigations on basic construction variables without conclusive results. These studies focused on determining the differences and similarities across class, and the differences and similarities of sprinters and distance racers. Few differences were found because: 1) many athletes compete in both sprints and distance races; and, 2) racing wheelchairs are highly individualized.

Cooper (19) described the basic principles behind racing wheelchair design, but did not present a detailed analysis. In general, there is the classical trade-off between weight and rigidity when designing a racing wheelchair. Because the available power of the athlete is small, energy loss between the athlete and the ground must be minimized (but with a restriction on the additional weight of the chair). Racing wheelchairs weigh between 4.5 and 7.3 Kg, with the center of gravity nominally located along the center line. The most commonly used materials for frame construction are *Chromolly* steel (SAE 4130) and aluminum (SAE 6061). These materials are readily available, have good strength-to-weight ratios, and are easy to work with.

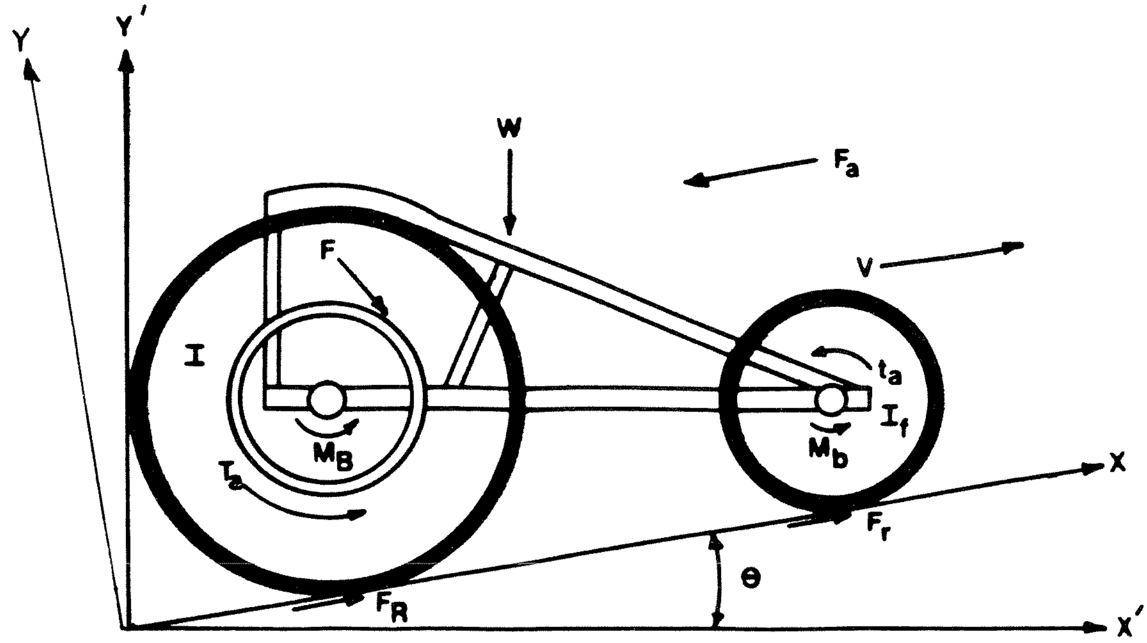

**Figure 5a.**
Free-body diagram for the motion of a racing wheelchair on a flat road (no road crown or irregularities).

The use of advanced composites has been investigated to a limited extent, primarily by Lawrence Livermore National Laboratories, the University of Delaware, and California Polytechnic State University at San Luis Obispo, but nothing has yet been published in this area. Golumbek[2] performed some preliminary investigations of several design factors for racing wheelchairs: finite element analysis of rear axles, and the design of a carbon fiber frame. He found that a 17-mm axle would provide a significant reduction in the axle-bending moments. Cooper has investigated the problem of rear wheel alignment (18), crown compensation (directional stabilization due to road crown) (16), and the use of frame geometry in directional control (14).

Researchers at the University of Virginia have investi-

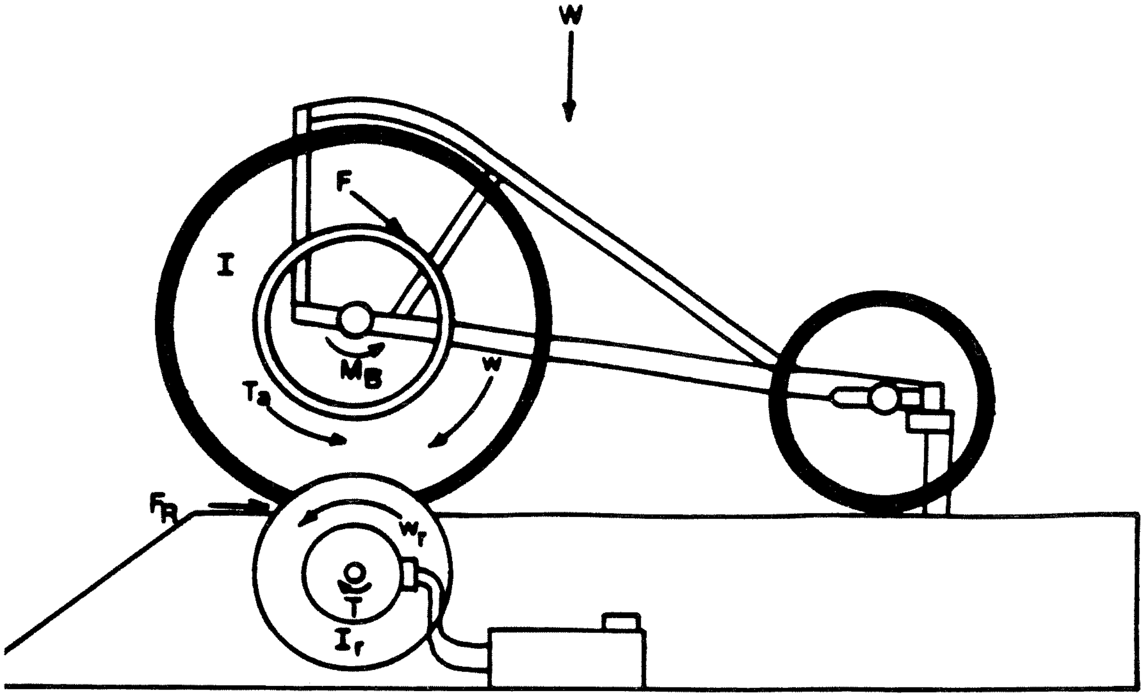

**Figure 5b.**
Free-body diagram for the motion of a racing wheelchair on an inertial dynamometer.

gated the various functional aspects of standard wheelchairs (5,6,7,11,47,48,49). **Figure 6** shows a photograph of a standard wheelchair. Although the results of their studies are not directly applicable, their methods form a basis for possible further investigation of racing wheelchairs.

Papers have been written on the stability of standard wheelchairs (11,76), but the stability of racing wheelchairs has yet to be investigated. It was found that front caster wheelchairs are directionally more stable than rear caster wheelchairs. This information may be useful in determining the solution to two problems facing wheelchair racers: At what speed does the racing wheelchair become laterally unstable? (**Figure 7**); and, What are the acceptable turning radii for various speeds in order to maintain roll stability? (**Figure 8**). Typically, when a vehicle becomes laterally unstable, it will rapidly veer off course if there is no steering. If someone is steering, the vehicle (if it has exceeded the stability limit) will oscillate back and forth about the desired heading until it goes off the road or track. This happens because the pilot tries to correct for the change in heading, and oversteers. Lateral instability primarily depends upon visibility, reaction time, task complexity, and the vehicle dynamics. Roll stability is also of particular importance. Racing wheelchairs (and their users) have been observed to roll over (flip) while turning, especially while going down a hill. Without a human pilot, the wheelchair will fall onto its side when speed is too great for the turn.

**Figure 6.**
Photograph of a standard sports wheelchair.

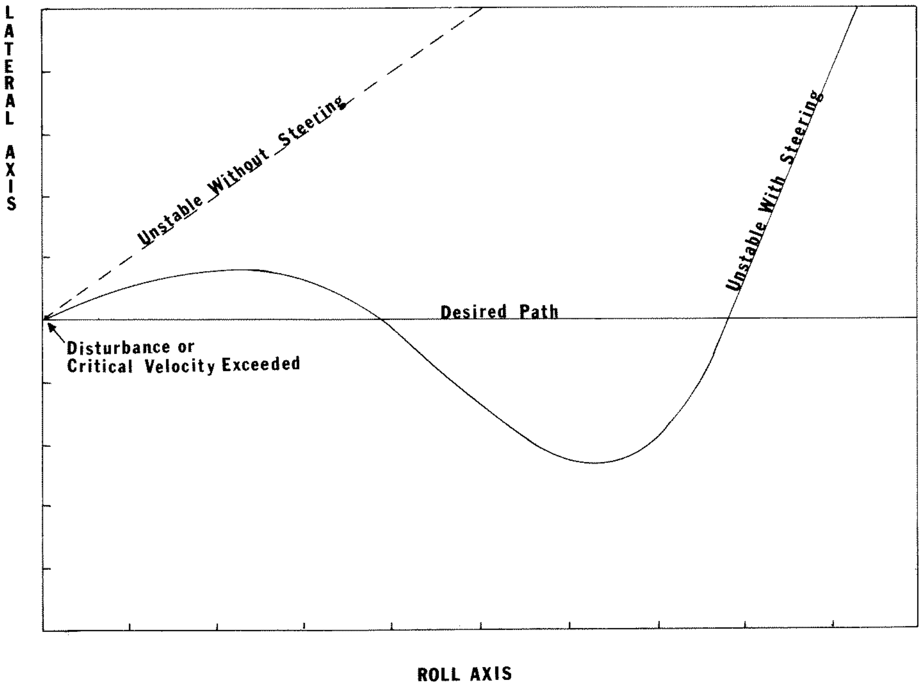

**Figure 7.**
A graph showing potential lateral instability curves for an impulse type disturbance (a wind gust acting upon the side of the individual/ wheelchair). —— Instability curve assuming steering. – – – Instability curve without steering.

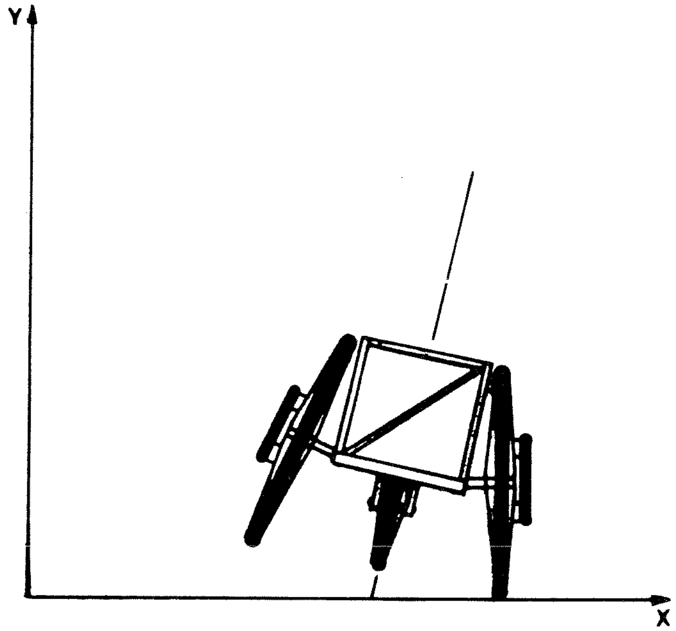

**Figure 8.**
Roll instability diagram. (Roll instability is described by the dynamics that determine when a chair will roll over or flip.) x = pitch axis; y = yaw axis.

With a human pilot, the wheelchair may bounce from balancing on one side of the chair to the other (because of the steering, as in the lateral stability case). If the individual is able to control the chair, the oscillations will dampen out (the chair may not be heading in the desired direction but will be balanced on all of its wheels); if not, the wheelchair/individual system will fall on its side. The relative stability of three- and four-wheel configurations is of particular interest.

Racing wheelchairs are highly individual. The factors determining the selection of the proper chair for an individual are not completely understood. In most cases, experience is the most appropriate tool.

More in-depth analyses of racing wheelchairs need to be performed to determine: 1) the location and magnitude of the stresses and forces acting upon the frames and the components; 2) the optimum steering geometry; and, 3) the magnitude of aerodynamic losses. These analyses should establish where improvements can be made and, where possible, failures can be prevented. Studies need to be performed to determine product life span and maintenance requirements. The tools of Finite Element Analysis need to be exploited to a greater extent. Dynamic stability analyses of racing wheelchairs need to be performed, evaluating various racing wheelchair configurations (four-wheeled chairs versus three-wheeled chairs) under a wide range of circumstances (down hills, turning, road surface irregularities, and interaction with other competitors). These studies must eventually account for the user control.

## CLASSIFICATION OF WHEELCHAIR ATHLETES

**Figure 9** presents a graphic explanation of the classification system used by the NWAA. There are seven classes (3 quadriplegic and 4 paraplegic) and open (classless) competition. Each of the seven classes is designed to represent an ascending level of physical ability.

Wheelchair athletes are classified by functional potential in order to encourage fair competition among individuals with similar levels of mobility impairment as related to manual wheelchair propulsion. Classification has been a source of controversy since its inception, because if an athlete is misclassified he/she may have an unfair advantage over fellow competitors. Problems arose in the mid-1950s when people began to notice that a single class for all wheelchair users was not equitable (quadriplegics never won any races in which paraplegics were involved). The number of classes has changed several times. There has been considerable discussion, but little scientific research concerning: 1) the basis upon which a classification system should be founded; and, 2) what constitutes a significant difference in potential needed to propel a racing wheelchair (20,25). Most of the reported research is concerned with methods of evaluating athletes under the present classification system. Weis and Curtis (77) and McCann (55,56) have written reviews on the controversies surrounding the classification of wheelchair athletes.

At present, the problems of classification are focused on the reduction in the number of classes and on the incorporation of athletes from multiple-disability groups. Organizers of large international events profess that the number of classes must be reduced in order to make wheelchair racing more understandable to the public (thus generating greater interest in it as a spectator sport), and because the logistics of organizing "so many" races is prohibitive. Others claim that competition becomes meaningless when there are so many classes, and no one wishes to see athletes discouraged or eliminated from competition by an unjust classification system.

Recently, the focus has been on various ways of developing a functional classification system in which athletes are classified by their potential ability to compete in the sport for which they are being classified. In contrast, the present system focuses on classifying people into "similar" degrees of disability. Functional classification emphasizes each athlete's physiology, whereas the present system emphasizes each individual's anatomy. The contro-

## CLASS IA

All cervical lesions with complete or incomplete quadriplegia who have involvement of both hands, weakness of triceps (up to and including grade 3 on testing scale) and with severe weakness of the trunk and lower extremities interfering significantly with trunk balance and the ability to walk.

## CLASS IB

All cervical lesions with complete or incomplete quadriplegia who have involvement of upper extremities but less than 1A with preservation of normal or good triceps (4 or 5 on testing scale) and normal or good finger flexion and extension (grasp and release) but without intrinsic hand function and with a generalized weakness of the trunk and lower extremities interfering significantly with trunk balance and the ability to walk.

## CLASS IC

All cervical lesions with complete or incomplete quadriplegia who have involvement of upper extremities but less than 1A with preservation of normal or good triceps (4 or 5 on testing scale) and normal or good finger flexion and extension (grasp and release) but without intrinsic hand function and with a generalized weakness of the trunk and lower extremities interfering significantly with trunk balance and the ability to walk.

## CLASS II

Complete or incomplete paraplegia below T1 down to and including T5 or comparable disability with total abdominal paralysis or poor abdominal muscle strength (0-2 on testing scale) and no useful trunk sitting balance.

## CLASS III

Complete or incomplete paraplegia or comparable disability below T5 down to and including T10 with upper abdominal and spinal extensor musculature sufficient to provide some element of trunk sitting balance but not normal.

## CLASS IV

Complete or incomplete paraplegia or comparable disability below T10 to and including L2 without quadriceps or very weak quadriceps with a value up to and including 2 on the testing scale and gluteal paralysis.

## CLASS V

Complete or incomplete paraplegia or comparable disability below L2 with quadriceps in grades 3-5.

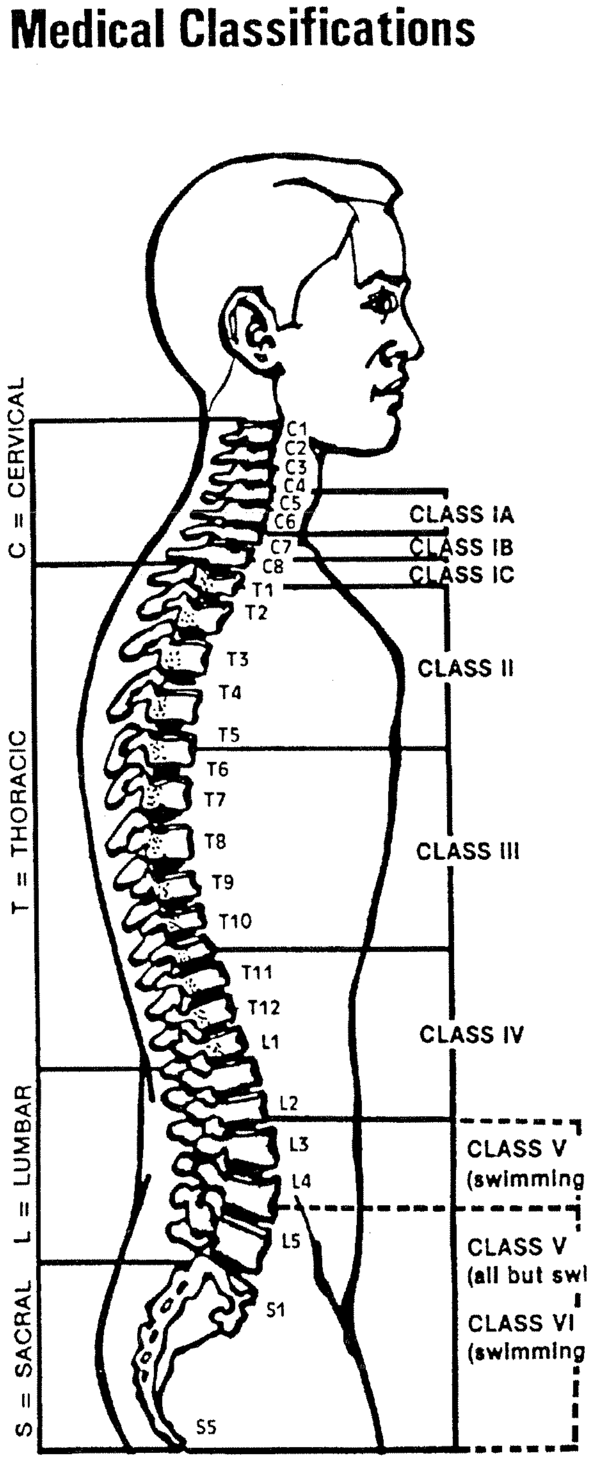

**Figure 9.**
A graphic explanation of the classification system used by the National Wheelchair Athletic Association. (*Permission granted.*)

versy stems from defining a significant difference in ability to propel a racing wheelchair or in performance. Coutts (22) has proposed the development of new methods of classifying athletes based on performance and evaluations by trained observers. His proposal would reduce the number of classes from seven to four (two quadriplegic and two paraplegic).

The ISMGF Athletics Committee is considering a proposal for a classification system that could be used to allow wheelchair athletes of all types (amputee, cerebral palsy, and spinal cord injured) to compete together. In addition, the proposal would reduce the number of paraplegic classes from four to two. Under the new system, athletes would first be classified by a medical team who would place each athlete in a class based upon level of impairment. Secondly, a trained observer (e.g., coach, official) and an experienced athlete (with recent experience, but not entered in the same competition) would evaluate the athlete being classified during preliminary rounds. Then the athlete would be placed in the class where his/her stroke kinematics, range of motion, seating position, and any other factors were most similar.

A more scientific basis for classification could involve a standardized exercise test, in addition to the methods listed in the previous paragraph. Athletes could be given a standardized maximal exercise test and/or anaerobic power test to help determine the "best" classification. The greatest foreseeable problem with this method (besides time and cost) is the high dependence upon training which may outweigh any disability-related factors.

## BIOMECHANICS OF RACING WHEELCHAIR PROPULSION

The study of the biomechanics of racing wheelchair propulsion is a fairly new interest. Most of the published research appeared after 1980, and was based on the use of high-speed film.[3] Some of the tests were conducted in the laboratory while others were conducted on running tracks.

A typical four-link (wrist/hand, lower arm, upper arm, trunk) kinematic model used in biomechanical analyses of wheelchair racing is shown in **Figure 10.** The most commonly cited kinematic analyses are those of Higgs (43), Ridgway, *et al.* (61), and Sanderson and Sommer (62). **Figures 11a** and **11b** show typical joint trajectories during steady state in Cartesian coordinates. Each of these studies and a recent study by Cooper (13) have investigated the cycle time (the total time for each stroke). The percent of the cycle time spent in propulsion and recovery for each of these studies is presented in **Figure 12.** The mean percent cycle time at about 6 m·s$^{-1}$ for all of these studies spent in propulsion was 36.25 percent, and in recovery was 63.75 percent.

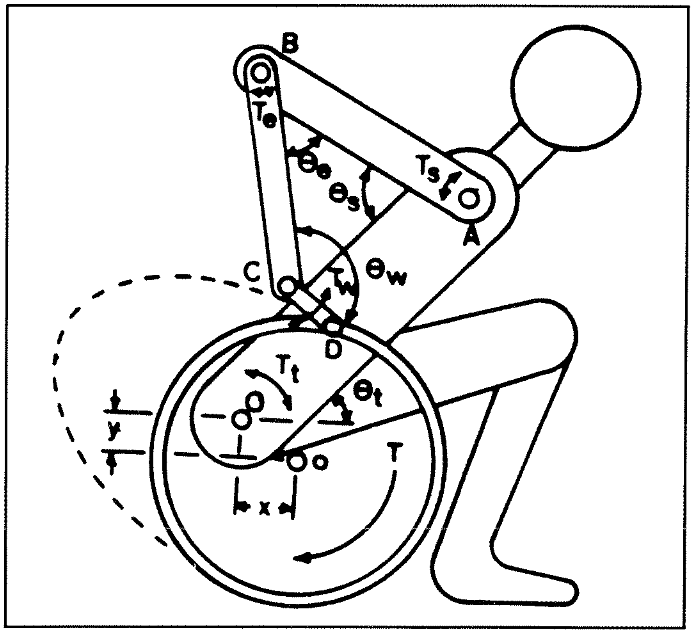

**Figure 10.**
A four-link kinematic model for biomechanical analysis of racing wheelchair propulsion.

The results of Ridgway, *et al.* (61) show that different levels of injury have distinct differences in their stroke kinematics with more potentially-able athletes (athletes of higher class) exhibiting less head movement (Class II/III showed 13.9 degrees while Class IV/V showed 9.2 degrees) and greater trunk movement (Class II/III showed 3.45 degrees while Class IV/V showed 7.8 degrees) during propulsion. This is probably a result of athletes attempting to generate greater propulsive force at the push-rings by imparting some momentum from their trunk to the push-rings. The more severely mobility-impaired paraplegics show more head movement because of the reduced functional control of the trunk, thus transferring momentum to the push-rings via head movement. In addition, the thighs of the Class IV/V athletes were positioned further from a vertical reference line than the other classes (IA/IB 32.18 degrees, II/III 37.60 degrees, IV/V 50.30 degrees).

Van der Woude, *et al.* (72,73) have suggested that the stroke kinematics are related to push-ring diameter, speed, work load, and fitness of the athlete. There is some indication that various push-ring diameters result in different demands on the athlete's body, and that optimum shoulder position is a function of push-ring diameter and the level of fitness of the athlete. They also found that the energy expenditure increases with push-ring size for the range from

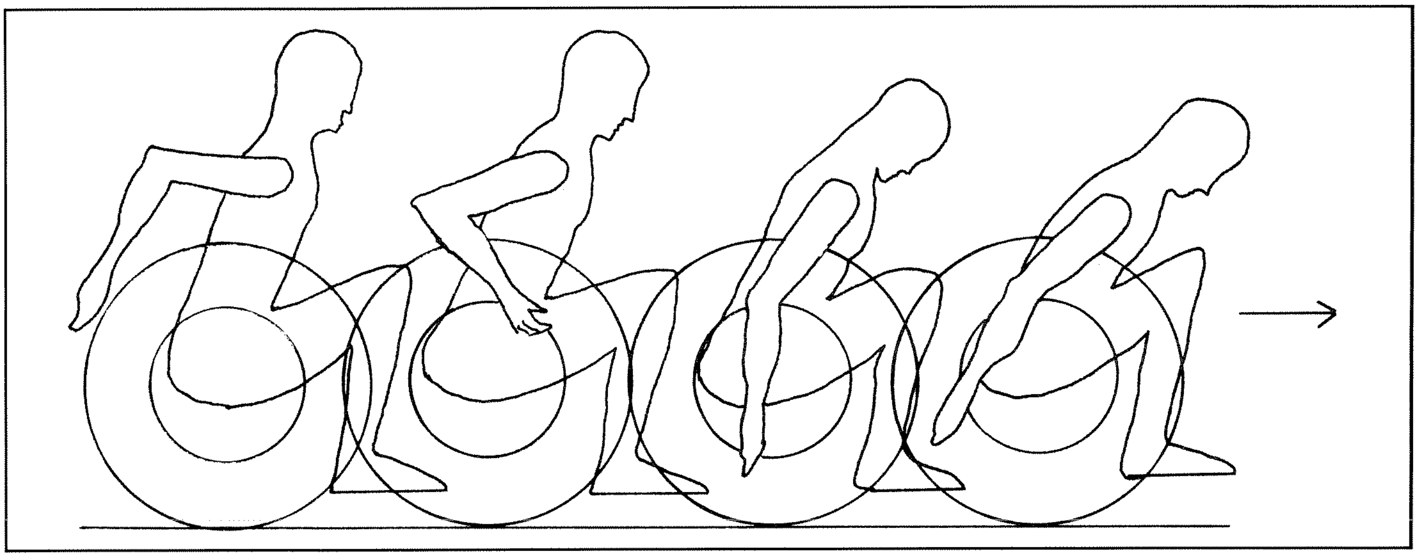

**Figure 11a.**
A representation of the arm movements during wheelchair racing.

0.3 to 0.56 meters of racing wheelchair push-ring diameters. A maximum efficiency of 6.7 percent was obtained for the large push-ring as compared to 7.9 percent for the smallest push-ring at speeds of 2.5 m•s$^{-1}$. These results may be biased by the push-ring diameter the subjects are accustomed to, and by the position of each individual's shoulders with respect to the push-rings.

Walsh, *et al.* (74,75) have suggested that the ability to achieve higher pushing frequency during the sprint start is related to the rate of acceleration, and in the acceleration phase the path of the hand during the follow-through should be along the push-ring. They found that during acceleration their subjects used cadences of between 100 to 150 strokes per minute; at constant speeds, cadences of between 50 and 80 strokes per minute were observed. The difference in power transmission for various push-rim and wheel diameters is often not measured or reported. This may be done by calibrating the ergometer, dynamometer, or treadmill for power output and then accounting for the gear ratio of the wheelchair. This could be as simple as reporting the workload, wheel diameter, and push-rim diameter.

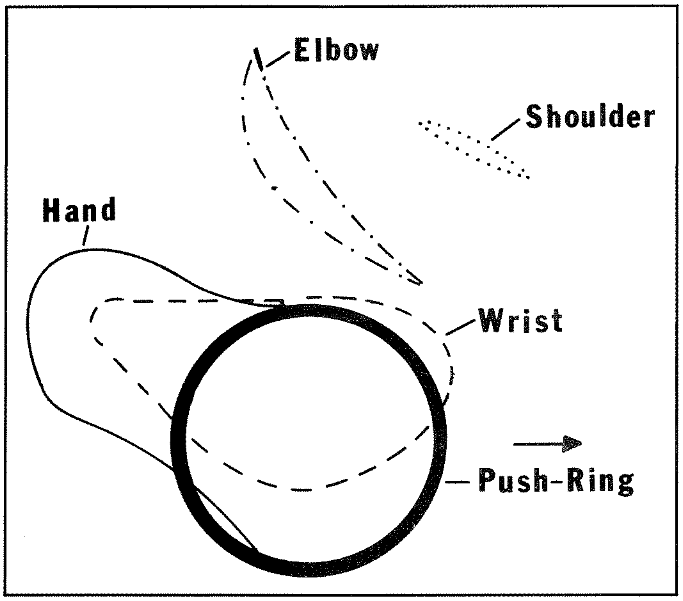

**Figure 11b.**
Example joint trajectories during racing wheelchair propulsion.

There are several factors which influence the determination of an optimum of such complex human/machine systems: 1) the effects of training or accommodation to the experimental station; 2) the adaptation of the subjects to changes made by the investigators; 3) the complex coupling of many factors (when one thing is changed it affects several other things), preventing the complete decoupling (separation so that we know the change was a direct result of the variable we are studying) of any one variable from another; and, 4) preventing the direct correlation of the change in one variable to the change in another. (How do we know the change was due to the factors we are studying and not due to something else, or is there a temporary effect that may improve, or a detriment performance that does not reflect the long term effect?) For example: if one proposes to determine the effect changes in push-ring size have on speed, the problem is complicated by the change in the shoulder position with respect to the various push-ring sizes. The anthropometric measurements of each indi-

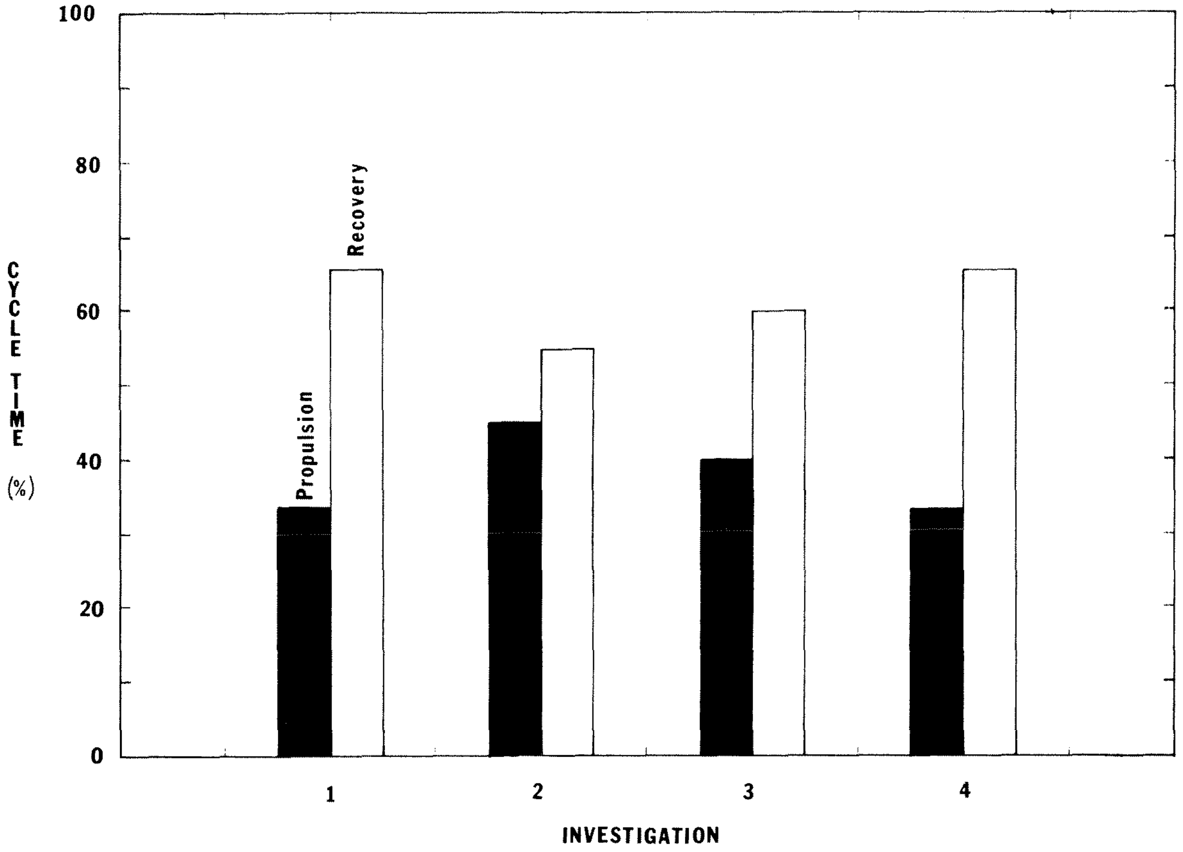

**Figure 12.**
Bar graph showing the percentage of the total cycle time spent in propulsion and recovery. (1 = Ridgway *et al.*; 2 = Higgs; 3 = Sanderson and Sommer; 4 = Cooper)

vidual influence the results as well as the effects of training (in general, an athlete will be most efficient with a pushring nearest the size used on his/her racing chair in the short term, but this may not be the athlete's optimum pushrim size).

Tupling, *et al.* (71) studied the efficiency of grab and strike starts and determined that grab starts are most efficient (grab starts produced an average impulse of 152.6 N•s, whereas strike starts produced an average impulse of 119.5 N•s). In addition, they determined that starting ability (impulse scores) were correlated to maximum strength (r=0.89, n=8).

Analyses of muscle fiber types for the prime movers have been conducted to a limited extent and suggest there may be a correlation between the ratio of the muscle fiber types and the potential to be competitive in a particular sport (68,69). The prime movers for wheelchair racing were identified to be the anterior deltoid, the pectoral, and the triceps muscles. Tesch and Karlsson (69) found that the wheelchair athletes they tested had 47±12 percent fast twitch muscle fiber, and a ratio of fast twitch fiber area to slow twitch fiber area of 1.61±0.44 with 58±10 percent of the total area represented by the fast twitch muscle fiber.

The analysis of the athlete/wheelchair interaction has been limited because many factors could not be measured. High speed filming is limited because it does not give an accurate reflection of the actual propulsion cycle (only the point of contact can be estimated and not the point where a propulsive force is initiated), nor is there any information concerning the magnitude and direction of the forces.

Treadmill testing is limited because the recovery phase of the propulsion cycle is modified. Some investigators have attempted to circumvent this problem by filming the individuals on the track; however, this is also limited because when using a fixed camera position only a short window (about five meters) can be observed.

Evaluating the biomechanics of wheelchair propulsion has been limited by the available instrumentation and the apparent lack of coordination between investigators of different disciplines (13,26). Most investigators of manual wheelchair propulsion have no means of measuring the three-dimensional forces/torques impelled on the push-rim by the individual. The California State University at Sacramento presently has a set of racing wheelchair wheels capable of measuring the three-dimensional forces and torques acting upon the push-rims. The Hines Department of Veterans Affairs Rehabilitation Research and Development Center is working with the University of Illinois at Urbana-Champaign to develop a set of wheels for a typical everyday-use wheelchair capable of measuring the three-dimensional torques and forces. Wright State University has a wheelchair ergometer capable of measuring push-rim torque.

Instrumentation needs to be developed to measure and record acceleration, speed, and work during actual racing or training. More sophisticated dynamometers need to be developed to simulate racing and training conditions. Instruments need to be developed to study the effects of wind, bearing, and rolling resistance.

## TRAINING AND COACHING OF WHEELCHAIR RACERS

Training and coaching of wheelchair racers is probably one of the most neglected areas of wheelchair racing science and medicine. Little information has been disseminated on effective coaching and training techniques; in this light, the athletes' progress since the inception of wheelchair racing in 1961 is impressive.

With the growing interest in wheelchair sports, an interest rose in the effect different types of training had on wheelchair racing performance (21,23). Hedrick, *et al.* (40) have prepared a manual on wheelchair sports for the Paralyzed Veterans of America using techniques adapted from running and cycling, as well as experience accumulated at the University of Illinois, Urbana-Champaign. The manual briefly covers seating and positioning, biomechanics, sports medicine concerns, nutrition, and training programs.

Dreisinger and Londeree (27) have written a review on wheelchair exercise that contains useful information on training for fitness. Steadward and Walsh (65) have published a review on wheelchair training strategies past, present, and future.

A few papers have been published on strength training,[4] showing it to be an important supplement to wheelchair training, and providing some useful training routines (30). Gross investigated the effect fitness training has on the strength and endurance of quadriplegic individuals, and found that regular training can increase respiratory fitness.(33) In general, most of the rules for training ambulatory athletes apply to wheelchair athletes as well. Clearly, upper-body strength is important to all physical sports, and aerobic training is required for success in endurance events.

A survey of the training practices of elite wheelchair road racers conducted by Hedrick, *et al.* (39) showed that most athletes rely on each other for information concerning training and that they follow no structured training program. They found that elite male racers train an average of 63 minutes per day for 6.8 workouts per week (74 miles per week) over the entire year, with the maximum amount of time spent training during April through June, and the minimum during October through December. Women train an average of 70 minutes per day for 5.7 workouts per week (54 miles per week) over the entire year, with the maximum amount of time spent training during October through December, and the minimum during April through June. Most athletes generally practice good health with regard to the use of tobacco, alcohol consumption, diet, and weight control (9). Few wheelchair athletes are coached formally, in contrast to able-bodied athletes, which suggests an area for future advancements in the sport (31).

As in any type of sport involving direct competition, strategy plays an important role in wheelchair racing. There has been very little published on this subject (64) and this lack of available information has had a noticeable effect on wheelchair race results. In international competitions, teams training regularly under experienced coaches often try to force the development of strategical races; then, by dictating the strategy, gain an advantage over other competitors.

Some research has been involved with the effect of nutrition on performance; preliminary results suggest this should be of greater concern to the wheelchair athlete.[5] These studies imply that wheelchair racers understand little about nutrition for competition (39,40). Nutritionists suggest that good dietary habits developed for able-bodied athletes also would be effective for most wheelchair racers.

The first works concerning the positive psychosocial aspects of wheelchair sports[6] were produced during the 1970s (4,54). Psychological profiles (the Profile of Mood State, and State-Trait Anxiety Inventory) of elite-level wheelchair racers and elite-level able-bodied athletes are similar (41,44,57).

Sports have been shown to have a positive influence on the psychological rehabilitation of the mobility-impaired by improving self-image and self-esteem, and by being an outlet for anger and frustration (34,35,36,45). Wheelchair sports and racing help mobility-impaired persons focus on the positive aspects of their lives rather than dwelling on the negative aspects; thus helping them adjust to the changes in their lives (8). Wheelchair athletes tend to be better adjusted to their disability[7] than do their nonathletic counterparts (58,63). Sports are also a vehicle for improving the able-bodied population's perception of the wheelchair user. The abilities and natural desires of wheelchair users to succeed and be recognized for their accomplishments (on an equal basis with their able-bodied peers), along with the ability of some of them to meet or exceed the performances of their able-bodied peers[8] has earned them greater respect and understanding for their accomplishments, rather than for their courage and fortitude (37,38).

With the increased drive to succeed in sports, primarily in wheelchair road racing where substantial amounts of prize money are available, wheelchair athletes have become more interested in sports psychology and a small amount of information directed at them has been published. These athletes have many of the same concerns and goals as their able-bodied peers and use the same tools from sports psychology to improve their performance (i.e., visualization, focusing, concentration, techniques to relax, etc.) (1,2,3,32,51).

Organized wheelchair sports teams are still generally associated with rehabilitation centers (50,66,67). Although this is an effective means of introducing newly-injured individuals to wheelchair sports, it may not be the best situation for developing "elite" wheelchair athletes. At rehabilitation centers, resources to hire a trained, full-time coach specializing in wheelchair sports are often not available. Most experts in exercise physiology, sports medicine, sports science, and engineering are not associated with rehabilitation centers. This removes the wheelchair athlete from potentially valuable resources and distances the expert from the sport. A more scientific approach to training should be developed so that wheelchair athletes can achieve higher performances, and have long healthy athletic careers with a minimum risk of injury. The health benefits and risks of wheelchair racing and training need to be studied in greater detail and with a broader subject population. An injury register should be developed to make data on safe training and racing habits available to athletes, coaches, trainers, and physicians.

## SUMMARY AND CONCLUSIONS

Future investigations of wheelchair racing science must take an interdisciplinary approach. There is much to be understood about the interaction between an athlete and his/her racing wheelchair and the interaction of the athlete/wheelchair system with the environment. These complex problems require an understanding of engineering, physiology, and biomechanics.

A substantial body of knowledge exists concerning racing wheelchair sports science and medicine. Investigations cover a wide range of topics, as is expected of any multidisciplinary subject. Much of the work is difficult to compare due to the lack of consistent procedures from one investigation to another. The data presented in the literature are often incomplete.

It is critical, when reporting results of experiments with wheelchair racing athletes, to report the size of the propulsion wheels, the size and shape of the push-rings, the type of contact surface used on the push-rings, and the type of contact surface on the gloves used. It is also important to include the dynamic location of the shoulder in relation to the rear axle in studies of the biomechanics of wheelchair propulsion and, most importantly, when varying any of the wheelchair parameters (i.e., the push-ring size, axle position, etc.). Studies need to be more consistent in their definition of a racing wheelchair and an elite athlete.

Wheelchair sport science is still in its adolescence, but a basis for future investigation has been established. Most of the investigations thus far have been concerned with studying male paraplegics (they constitute an overwhelming majority of wheelchair racers): future studies need to include female and quadriplegic wheelchair athletes.

Much remains to be investigated in all of the areas discussed in this review. Mathematical modeling and analysis, computer simulation, and the engineering of more sophisticated test equipment are crucial to the continued development of this field.

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