Adaptive Sports Technology and Biomechanics: Wheelchairs

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Wheelchair sports are an important tool in the rehabilitation of people with severe chronic disabilities and have been a driving force for innovation in technology and practice. In this paper, we will present an overview of the adaptive technology used in Paralympic sports with a special focus on wheeled technology and the impact of design on performance (defined as achieving the greatest level of athletic ability and minimizing the risk of injury). Many advances in manual wheelchairs trace their origins to wheelchair sports. Features of wheelchairs that were used for racing and basketball 25 or more years ago have become integral to the manual wheelchairs that people now use every day; moreover, the current components used on ultralight wheelchairs also have benefitted from technological advances developed for sports wheelchairs. For example, the wheels now used on chairs for daily mobility incorporate many of the components first developed for sports chairs. Also, advances in manufacturing and the availability of aerospace materials have driven current wheelchair design and manufacture. Basic principles of sports wheelchair design are universal across sports and include fit; minimizing weight while maintaining high stiffness; minimizing rolling resistance; and optimizing the sports-specific design of the chair. However, a well-designed and fitted wheelchair is not sufficient for optimal sports performance: the athlete must be well trained, skilled, and use effective biomechanics because wheelchair athletes face some unique biomechanical challenges.

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INTRODUCTION

Wheelchair sports are an important tool in the rehabilitation of people with severe chronic disabilities and have been a driving force for innovation in technology and practice. Through adaptive sports, people with impairments learn compensatory strategies and to transform their perceptions of self [1]. Sports and recreation for people with impairments build strength, flexibility, stamina, and an improved outlook on life [2]. As the adaptive sports opportunities have expanded, so have the expectations of people with impairments. Furthermore, adaptive sports have created opportunities for greater community integration, especially with activities that allow people with and without disabilities to participate together. The wheelchair sports movement parallels the disability rights movement, and both have complimented each other in making advances for promoting respect, dignity, and inclusion for people with impairments.

Here we will present an overview of the adaptive technology used in Paralympic sports. The focus is on wheeled technology and the impact of design on performance. In the context of this paper, performance includes achieving the greatest level of athletic ability and minimizing the risk of injury. The wheelchairs used for basketball, rugby, tennis, softball, power wheelchair soccer, racing, and handcycling are described, along with some of the key considerations for their design and fitting to athletes.

Many advances in manual wheelchairs trace their origins to wheelchair sports. Features of wheelchairs that were used for racing and basketball 25 or more years ago have become integral to the manual wheelchairs that people now use every day [3,4]. Frame materials such as aluminum, titanium, and composite materials all were first introduced in the designs of sports wheelchairs to make them lighter and stiffer but ultimately faster and more responsive. These materials are now used widely in the design of ultralight manual

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wheelchairs for much the same reasons, except instead of improving sports performance they help to increase the ability to independently perform activities of daily living and reduce repetitive strain injuries. There are also similarities in the principles used in frame design, which make chairs easier to propel, allow for easier transport of the wheelchair in a vehicle and reduce upper limb strain.

The principles of wheelchair design and fitting are founded on the principles developed for wheelchair sports (Figure 1). In daily mobility wheelchairs as in sports wheelchairs, the driving principle is to create an efficient human-machine system in which the person and the wheelchair work in close coordination [4]. This system is accomplished by fitting the wheelchair closely to the body to form a fit akin to a shoe or a glove. A wheelchair is best perceived as an orthotic device and fitted to the user as such. This translates into making the seat fit closely, even snugly, to the body, ensuring that the backrest supports the spine and pelvis without imposing upon the movement of the scapula and arms, and the legs must be stable and the feet firmly supported. Through wheelchair sports, we have learned that the large wheels used for propulsion must be brought close to the body. This allows the arms to remain in a more neutral position, and the shoulder to remain in a stable position throughout the range of motion during the entire stroke-cycle [5].

The axle location of the drive wheels should be located just aft of a vertical line extending downward from the combined location of the center of mass of the user and the chair (Figure 1) [6]. This can be determined by adjusting the angle forward and having the person sit upright and lift his or her arms above the head; in this position, the chair should be on the brink of tipping, but still have all 4 wheels on the ground. This has multiple positive effects: (1) it allows the arms to grasp a larger portion of the pushrims to increase the stroke angle and reduce stroke frequency; (2) it balances the weight on the drive wheels and casters, such that the drive wheels carry more of the user's weight reducing the overall rolling resistance; and (3) it reduces the downhill turning moment of the person and chair, making it easier to propel the wheelchair in the presence of cross-slopes and to turn the chair.

Adding camber to the rear wheels was the result of necessity in wheelchair basketball and racing. Camber (the angle the wheels make with respect to vertical when viewed from the rear of the chair) was introduced in wheelchair basketball to increase turning responsiveness and stability, and to prevent opposing players from getting too close. It has the further benefit of protecting hands when 2 wheelchairs side swipe each other. Camber benefits wheelchair racing as well by allowing access to the greater portion of the pushrims without the arms hitting the tops of the wheels [7].

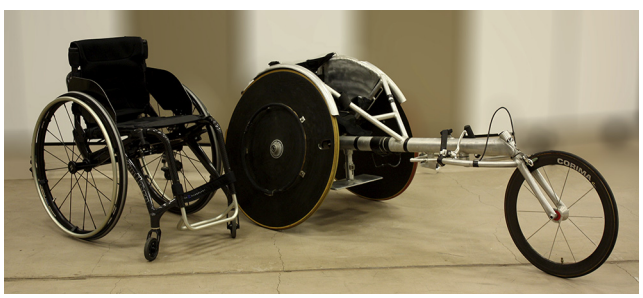

Figure 1. Carbon fiber ultralight daily use wheelchair (left) compared to the racing wheelchair (right).

The current components used on ultralight wheelchairs also have benefitted from technological advances developed for sports wheelchairs. The wheels now used on chairs for daily mobility incorporate many of the components first developed for sports chairs, including synthetic spokes of composite materials; high-pressure, low-resistance tires; sealed high-quality bearings to include ceramic bearings; and ergonomic pushrims. Ultralight wheelchair manufacturers also incorporate backrests and seats that use rigid, body-formed surfaces and adjustable tension, which have been commonplace in sports wheelchairs. Even race components such as road-crown compensators are making their way onto chairs designed for daily mobility.

Up until the 1980s, people participated in wheelchair sports by using essentially the same chairs that they used for daily mobility, sometimes with minor modifications such as smaller diameter pushrims, rear wheel camber, and lower seat height [4]. The growing number of opportunities for sports participation and competition led athletes to collaborate with engineers, designers, and manufacturers to create novel designs aimed at improving sports performance. This led to revolutionary changes in wheelchair design and at the same time fueled research into adaptive sport performance. Today, the design of wheelchairs is tailored towards each specific sports, resulting in dramatic improvements in sports performance.

PRINCIPLES OF DESIGN FOR SPORTS WHEELCHAIRS

There are some basic principles of sports wheelchair design that are universal across sports: (1) optimize the fit of the wheelchair to the user so that they act as one; (2) minimize weight while maintaining high stiffness; (3) minimize the rolling resistance; and (4) optimizing the sports-specific design of the chair. Most sports wheelchair frames use aluminum, titanium, or composite materials [8]. As features and components are added, most chairs use a variety of materials chosen for the specific purpose. Aluminum is widely used as it is lightweight, easy to work with, and readily available. Composite materials can lead to the best results but tend to be expensive and labor-intensive for fabrication; hence they are primarily used by athletes competing at the highest levels.

Basketball Wheelchair Design

Basketball is one of the oldest of wheelchair sports and is played in more than 100 countries around the world [9].

Basketball is played on a smooth flat court, and the purpose of the game is to maneuver the ball around the other team of players and score the most baskets. This has led to basketball wheelchairs constructed with 6 wheels: 2 swivel casters in the front; 2 drive wheels; and 2 swivel casters in the rear (Figure 2), This allows the drive wheels to be placed at or very close to the center of gravity of the basketball player, which makes the chair very responsive for turning and at the same time allows for efficient propulsion. Camber of up to 10° is added to increase side-to-side stability, speed, and turning responsiveness.

To improve performance, the feet are tucked under the seat, which shortens the chair and makes it turn quicker by reducing the angular moment of inertia. Ratchet straps are used to hold the athlete firmly in the seat and for some athletes their feet are strapped to the footrests as well; this helps to make the athlete and wheelchair act in concert. Shrouds are placed around the front of the frame to inhibit the ability of an opposing player trying to hook or pick a player either inadvertently or on purpose. Basketball wheelchair design is position specific. Forwards and centers often sit high as the rules permit for greater ease of shooting at close range to the basket, whereas guards lower their center of gravity to improve maneuverability.

Tennis Wheelchair Design

Tennis chairs have much in common with basketball wheelchairs. The goal of tennis is to hit or return the ball over the net such that the opponent is unable to return it; hence, quickness and maneuverability are critical [10]. Because the opposing player is on the opposite side of the net and no contact between players occurs during the game, the chair can be streamlined. Therefore, tennis wheelchairs have a single front and rear caster, in contrast to a basketball chair, which has 2 front and rear casters. Tennis chairs often have handles on the front of the seat in order to help the athlete stabilize their balance as they lean or extend to hit the ball with their racquet.

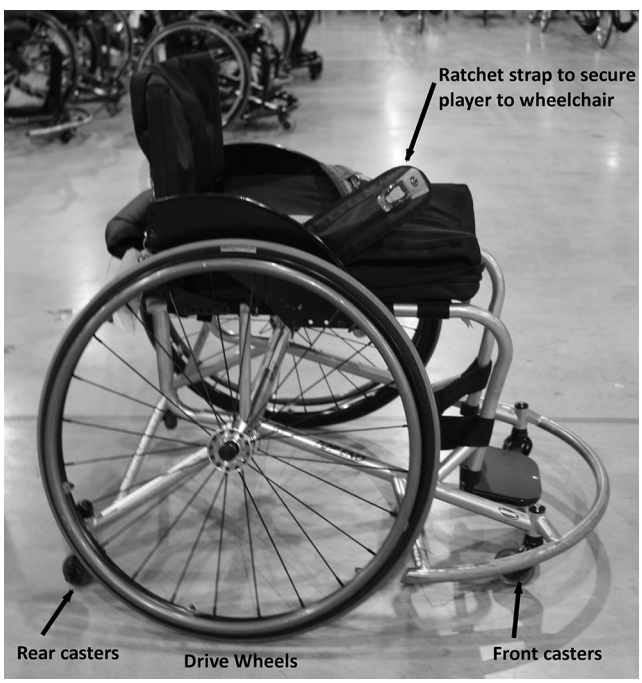

Figure 2. Wheelchair used to play basketball.

Softball Wheelchair Design

Wheelchair softball involves 2 teams with one on the field of play in a defensive posture and the other team batting and attempting to score by getting players on base [11]. Wheelchair softball is essentially the same as softball, with a few differences (Figure 3). The ball used in wheelchair softball is larger and softer so that players do not need to use a glove. The game is played on a firm and level surface, such as a parking lot. At this time, wheelchair softball players use basketball or tennis chairs to play. Players positioned in the infield are more prone to using basketball wheelchairs, because of the potential for contact with a player of their own or the opposing team.

Rugby Wheelchair Design

Wheelchair rugby is a high-speed and high-impact team sport [12]. Direct contact between the chairs of players is an integral part of the game, which differentiates it from other court sports played in wheelchairs. Furthermore, wheelchair rugby is limited to athletes with both lower and upper extremity impairments. These factors impose different design criteria on wheelchair rugby chairs, which has resulted in 2 basic styles of chair: offensive and defensive. Basically, players are divided into whether their mission is to score points or to protect their goal and prevent the other team from scoring points. Offensive players tend to be less impaired, and thus faster and more adept at maneuvering their chairs around the court. The basic frame design of a rugby chair is the same as that for a guard in wheelchair basketball. It has 6 wheels, with the drive wheels located near the center of mass. There is typically a large posterior seat angle to help hold the player in a stable position in the chair. The "V" formed by the legs and torso also serves to cradle the ball when being carried on a players lap and helps the player to recover after falling forward against their legs. Because of the frequent impact with other chairs, rugby chairs use solid wheel covers commonly made of aluminum to protect the spokes and to encourage other chairs to glance off upon contact.

The primary difference between offensive and defensive wheelchair rugby chairs is in the design of the added components (Figure 4). Offensive chairs are built with shrouds to make it more difficult for other players to obstruct their path or to hook them to impede their progress. In contrast, defensive

Figure 3. Batting in wheelchair softball.

chairs are designed with bumpers intended to capture the chairs of offensive players or at least disrupt their path.

Racing Wheelchair Design

Wheelchair racing is perhaps the oldest of all wheelchair sporting events. There are stories of veterans recovering from their wounds in World War I racing each other around the halls of Walter Reed Army Hospital [13]. In the 1980s, the racing wheelchair evolved to the point at which it was a completely custom device designed specifically for racing [4]. However, racing wheelchair design was limited from the late 1940s up until the 1990s by rule restrictions that severely inhibited design options [4]. Rule restrictions began to be lifted because of pressure from athletes and the growing scientific evidence that the rules may actually be placing athletes at undue risk for injury as well as artificially limiting the advance of the sport.

Some of the most important rule changes were as follows (Figure 5): removing the restriction for an overall length of 120 cm (48 inches); allowing for 3 wheels; and permitting steering gear (ie, a crown-compensator and steering lever). It turns out that these 3 rule changes interact with each other and have transformed racing wheelchairs. Removing the length restriction and allowing the use of a crown-compensator made the 3-wheeled racing chair design possible. For racing chairs to be stable with 3 wheels, they needed a longer wheelbase, and the crown-compensator further helped to stabilize the chair, especially at high speeds. This made it possible to use larger front wheels, and simpler, lighter, and stiffer frame designs that made racing much faster.

Racing wheelchairs currently have 3 wheels. The front wheel is typically about 20 inches in diameter, and the rear wheels range from 25 to 27 inches in diameter. Wheels are most commonly made of carbon-fiber composite. A T-frame design is most common, with one tube connecting the axles of the rear wheels with another tube welded at 90° from the midpoint of the axle tube to protrude forwards to terminate with the head-set bearing housing (Figure 6). The fork for the front wheel mounts to the head-set housing. The steering gear mounts between the fork and the forward pointing frame tube through a spring-loaded crown-compensator. The device is spring loaded to allow the athlete to overcome the springs for turning with their arms when using the steering lever. The crown-compensator is used to help keep the wheelchair straight when on a road or track with a cross-slope, but also helps the athlete to negotiate the curves of a track without

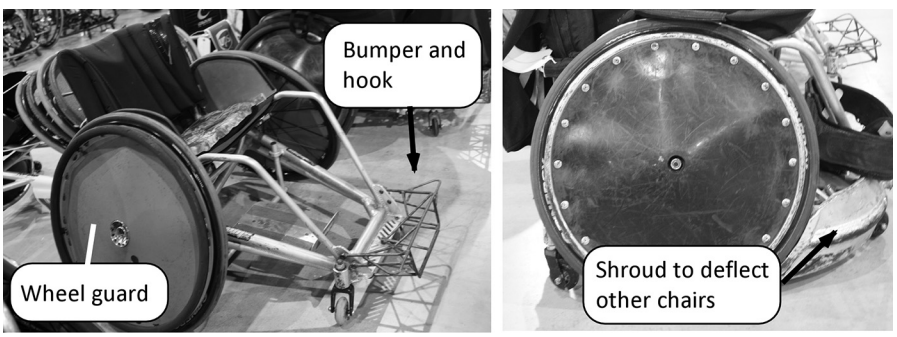

Figure 4. Wheelchairs used to play rugby with chair for defense (left) and offense (right). Players specialize in either defense or offense depending on their abilities and talents.

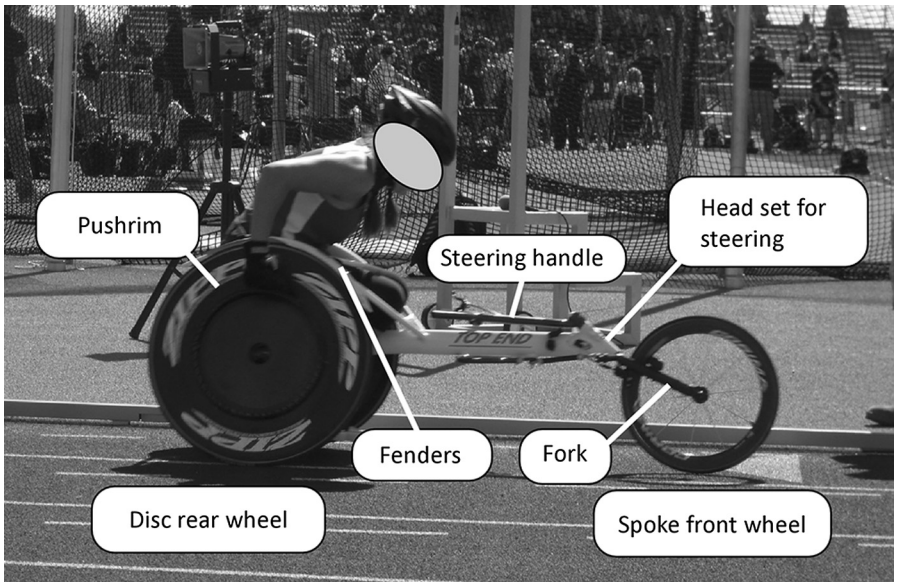

Figure 5. Racing wheelchair on a track with the key features labeled.

steering with their hands. This permitted considerable improvements in time as athletes could push equally with both arms around curves or in the presence of cross-slopes.

Racing wheelchairs use a kneeling position, where the athlete essentially leans forward with their chest close to their knees. This position allows maximum power to be transferred by the arms and trunk muscles to the pushrims. Pushrims are selected based on the length of the athlete's arms so that the athlete can reach the bottom of the pushrims before his or her arms are fully extended. The seat of a racing chair must fit tightly, much like a prosthetic socket, and straps are used to firmly lock the athlete into the seat.

Handcycle Design

Handcycles first started to be developed after World War I as a means for veterans to negotiate rough terrain and to travel longer distances [13]. It was not until the 1980s that races began to emerge and the sport started to grow. Much of the growth can be attributed to 3 factors: (1) there was a growing desire by people with impairments to participate in sports and recreational activities along side of their family and friends without disabilities; (2) many people with impairments could not effectively use a racing wheelchair because of their anatomy or impairments; and (3) triathlon was emerging as a sport and some people with impairments had a desire to participate.

Because of the origin of the sport, 4 basic designs of handcycles have emerged: (1) the arm-crank add-on unit that attaches to a person's manual wheelchair; (2) upright arm-crank units where the person sits much like they do in their wheelchair; (3) hand-cycles where the athlete sits in the kneeling position with the trunk upright or forward leaning above the cranks; and (4) recumbent devices in which the athlete lies on his/her back with the cranks placed above their chest. The most commonly used are recumbent and kneeling, and these are the only two used in the Paralympics (Figure 7). Most hand-cycles have multiple gears, ranging anywhere from 1 to 33. The different designs and availability of gears have made both recreational activity and racing accessible to many more people with impairments than ever before.

Power Wheelchair Soccer

There are few opportunities for people with high levels of impairment who use electric-powered wheelchairs to participate in sports, and the opportunities are even fewer for team sports. The creation of power wheelchair soccer opened a new avenue for people with upper and lower extremity impairments to compete in a dynamic team sport that requires little in the way of equipment or modification of their wheelchairs [14]. As the sport has evolved, some modifications to the athletes' chairs have advanced. The power soccer ball is approximately 0.5 m in diameter and is moved and manipulated with the athlete's wheelchair, typically with a shroud placed around the footrests. The shroud also serves to protect the athlete's feet. Inexpensive shrouds can be made of plastic that are helpful for people being introduced to the sport or who play at a recreational level. There are also custom shrouds, typically made from steel, that some players choose to use. As power soccer has matured and players' skills have advanced, there has become a demand to design or modify powered wheelchairs for soccer (Figure 8). Athletes have discovered that rear wheel drive chairs that are both fast and have a high rate of turning enhance performance. Unfortunately, most electric-powered

Figure 6. Racing wheelchair viewed from the bottom to show the T shape of the frame.

wheelchairs are mid-wheel drive and have less power than some models produced 15 or more years ago. Some athletes acquire older rear-wheel drive wheelchairs and have them refurbished and modified for power soccer.

IMPACT OF ADVANCED MANUFACTURING AND MATERIALS

Advances in manufacturing and the availability of aerospace materials have made it possible for the design of wheelchairs and their components to meet the demands of today's athletes and wheelchair sports. The 80-pound mild-steel wheelchair of the 1930s through the 1970s has no place in wheelchair sports today [15]. Although there remains hand craftsmanship in sports wheelchairs, the trend is towards modern manufacturing processes and design tools.

Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM)

CAD has become ubiquitous in the engineering and machine design communities. CAD has benefitted sports wheelchair design in several important ways [15]; it has improved the quality of sports wheelchairs by systematically defining component and subsystem tolerances, providing simulations for optimization of strength and stiffness, creating easily retrievable documentation, and providing files for CAM [16]. Probably the most significant contribution of CAD has been the application of parametric design that allows a basic design of a wheelchair to be scaled and customized to a particular athlete [17]. This has allowed sports wheelchairs to be fitted to meet each athlete's particular needs, talents, and preferences. With CAD software, a digital model can be created that allows engineers and designers to visualize how components fit together, to examine the final appearance, and to study how the chair will perform.

CAM is the sibling to CAD [18]. During the past 2 decades, manufacturing has transitioned from special purpose machines and custom tooling to flexible machines and computer programs. The market for sports wheelchairs is small, and therefore it was not cost-effective to develop specialized tooling and machines to fabricate sports wheelchairs. However, with CAM, this is no longer a barrier as fabricators and manufacturers use machines that can build a wide variety of components using software to guide the tool parameters (e.g., speeds, feeds, and pathways). Today, a single machine can make multiple parts simultaneously, potentially for different customers. As CAM machines become more affordable, they become accessible to local fabricators and are becoming available by simply uploading design drawings to a flexible manufacturer's website.

Design also has changed as traditional processes are converted to modern techniques such as water-jet cutting or laser cutting [19]. These machines can cut a variety of materials: cloth, metals, and plastics with little human effort. Through water-jet cutting or laser cutting, flat sheets can be cut in multiple parts with very complex shapes as easily as cutting a straight line. This allows engineers and designers to exercise greater creativity and complexity in their designs with little or no extra cost. CAD/CAM has been adopted by sports wheelchair designers and manufacturers to produce higher quality products and to improve performance. A significant advantage has been the availability of high quality sports chairs to a larger number of people, and the availability of off-the-shelf replacement parts.

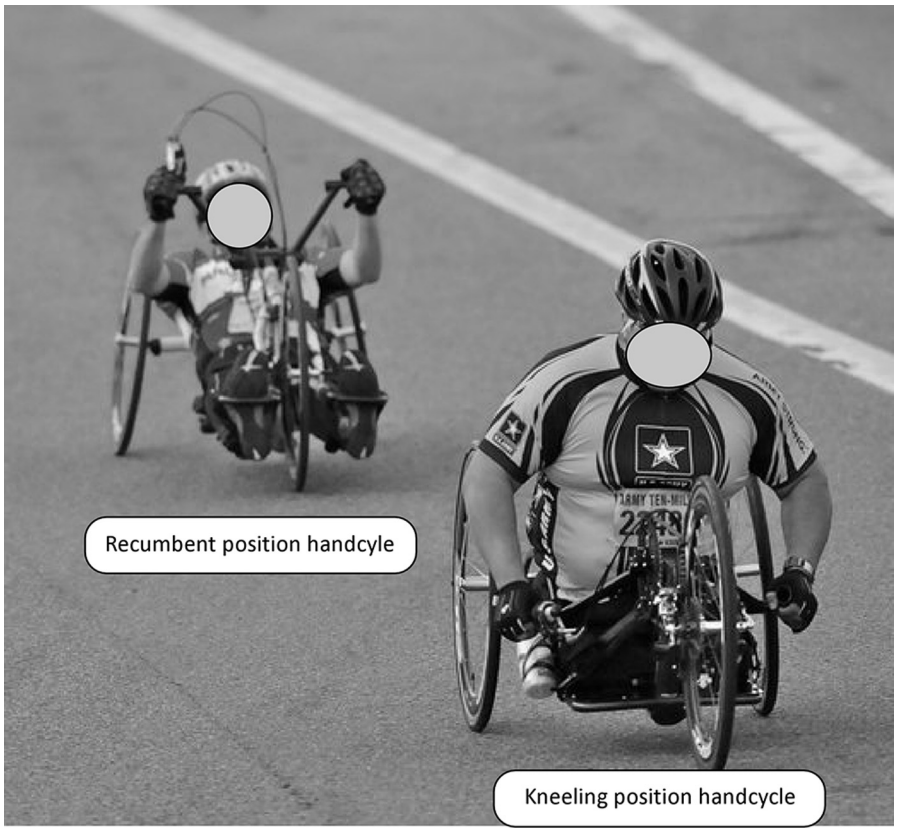

Figure 7. Recumbent and kneeling versions of hand-cycles.

The ubiquity of CAD has also led to a growing trend towards additive manufacturing, that in some cases allows the fabrication or "printing" of parts on a desktop [20]. This has allowed sports wheelchair designers to incorporate parts that would have previously required castings or molds that were cost prohibitive given the small number of sports wheelchairs and their parts sold. Currently, additive manufacturing is primarily used for plastic parts on sports wheelchairs, but as additive manufacturing becomes widely available and more thoroughly understood its use is likely to become more widespread and expand the types of materials applied.

Mixed Materials

Composite materials are the most well known and frequently used of the mixed materials. Materials such as carbon-fiber, Kevlar, fiber glass, S-glass, etc, are all synthetic materials that use a thermal or thermo plastic binding agent to form a composite that can be very light and very strong [21]. In wheelchair sports, one of the most striking examples is the hand-cycle used by Alex Zanardi to win a gold medal in the Paralympic Games. His hand-cycle used materials, designs tools, and fabrication processes adopted from automobile racing with outstanding results. Through additive manufacturing, there are new materials being created and new techniques to fuse materials to customize the properties of the resulting component. As this research progresses, it will be possible to select material properties of specific portions of a part being printed using additive machining; opening entirely new horizons for engineers and designers.

BIOMECHANICS OF WHEELCHAIR SPORTS

A well-designed and fitted wheelchair is necessary for optimal sports performance but not sufficient. The athlete must be well trained, skilled, and use effective biomechanics. Wheelchair athletes face some unique biomechanical challenges. Because wheelchair athletes use their arms for their sport as well as for mobility and activities of daily living, they need to exercise caution [22]. The average manual wheelchair user propels their wheelchair with nearly 1000 strokes per day at a net peak force of about 70 Newtons [23]. The frequency and level of force required for daily mobility places manual wheelchair users at risk for injuries to the wrist, elbow, and shoulder. Furthermore, some wheelchair athletes also have impaired sensation and or loss of muscle mass in the lower extremities, which places them at risk for pressure ulcers. Wheelchair athletes also are prone to the same types of overuse and sports-related injuries that affect other athletes. There remains a paucity of information about

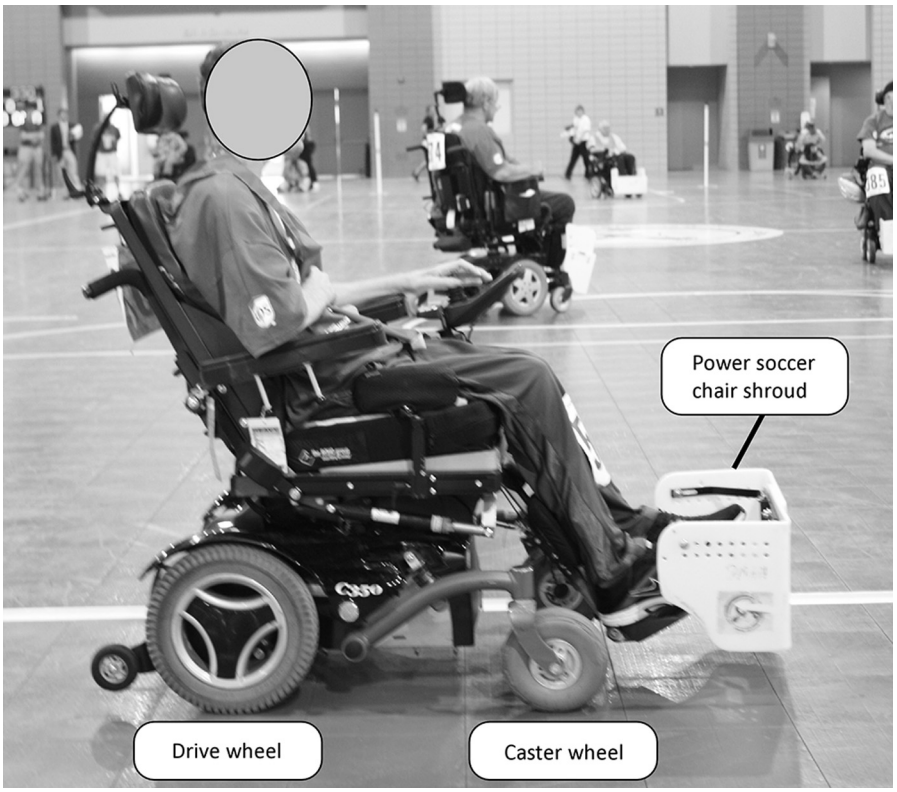

Figure 8. Electric powered wheelchair modified for soccer.

the biomechanics of wheelchair sports. Sports such as wheelchair basketball and racing have received greater attention than other sports.

Propulsion Biomechanics

There are some common biomechanical principles that are applicable across the sports involving pushrim wheelchairs. During pushrim propulsion the stroke is divided into two basic phases: propulsion phase and recovery phase [24]. The propulsion phase is when the hands are in contact with the pushrims. The efficiency of the stroke is determined by the following characteristics: the coupling of the hand with the pushrim at the beginning and ending of the propulsion phase; the push angle; the position of the shoulder at the beginning and ending of the stroke; and the recovery pattern. A circular pattern is most efficient during the recovery cycle [24]. When accelerating or turning, it is best to chop the stroke and reduce the recovery time. However, when going straight and fast, it is best to use a long and fluid stroke.

Maintaining muscle balance, especially around the shoulder complex, is essential for performance as well as reducing the risk of injury [25]. For example, in wheelchair racing it is important to have a high back swing during the recovery stroke so that the wrist and elbows reach maximum height, preloading the muscles before contact with the pushrim to begin the propulsion phase. This allows for maximum forces to be applied to the pushrims. However, if the posterior muscles have insufficient strength and endurance the arms begin to lower during the recovery phase, and the athlete begins to slow.

Seating Biomechanics

Seating for wheelchair sports has 3 basic goals: (1) provide a firm, snug, and efficient base of support for propulsion and control; (2) maximize the balance of the user for the sport activity; and (3) avoid promoting the development of pressure ulcers or other soft tissue injuries. The padding in sports wheelchairs is typically held to a minimum in order to promote the athlete and the wheelchair acting as one integral unit. The risk of soft-tissue injury is minimized by increasing the surface area of the seat in contact with the body. In some cases, the seat is molded to the user to form a custom seating orthotic. The large contact area and firm padding must closely fit the contour of the athlete's body in the seated position for the sport. Straps also are used to further hold the athlete firmly in place. In most wheelchair sports, with the notable exception of hand-cycling, athletes use seat dump (posterior tilt to the seat base) to push their back against the backrest, thus increasing stability. Seat dump also reduces

the angle between the thighs and the trunk which helps to improve balance and for ball sports provides a place to secure the ball.

Injury Prevention

Athletes cannot perform well when injured. The most common injuries to wheelchair athletes are abrasions, contusions, and injuries to tendons and ligaments [26]. Some features such as shrouds, wheel covers, and carefully fitted wheelchairs help to reduce these injuries. The wheelchair affords some level of protection, and injuries are reduced when athletes stay in their chairs during an accident, a tip, or a collision. There is little that can be done to reduce the risk of abrasions and contusions except to improve sport specific skill to avoid missed strokes, unintended collisions, falls, and other accidents.

Overuse and repetitive strain injuries of the upper extremities are common among athletes because they typically occur over long periods of time [27]. Research provides some guidance on how to reduce the risk of overuse and repetitive strain injuries. Paralympic sports injury epidemiologists are working with engineers and sports officials to make adaptive equipment and sports safer. The essential elements of preventing overuse injuries in wheelchair athletes are to keep the weight and rolling resistance of the wheelchair to a minimum, place the large wheels for propulsion as close to the center of mass of the athlete as is practical; use high pressure tires that are properly inflated; work on stamina, strength and flexibility of the arms and shoulders; apply proper training and sports performance techniques; and avoid increases in body weight.

CONCLUSION

Technology and how it is applied are critical to the success of wheelchair athletes. As Paralympic competition becomes more intense, it demands more sophisticated engineering to create advances in sports technology. Advances in manufacturing processes, computer simulations, and instrumentation promise to bring further improvements in adaptive sports technology performance and to reduce injures to athletes.

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