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SMARTWheel: From Concept to Clinical Practice

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Abstract

Background—Wheelchair prescription is complex with thousands of choices and options. Theoretically, a higher quality or innovative wheelchair that is appropriately matched to the user and their unique needs will increase participation. It is well accepted that there is an alarmingly high incidence of carpal tunnel syndrome, and rotator cuff injuries among manual wheelchair users.

Development—Since the initial conceptualization, the SMART^{Wheel} was intended to better understand the physiological and physical effects of wheelchair propulsion on the body. Initially, little was known about wheelchair propulsion and the SMART^{Wheel} transformed the nascent field of wheelchair propulsion biomechanics.

Impact—Although still an important area of clinical research, the SMART^{Wheel} has been critical to the study of the relationship between the type of wheelchair, set-up, activity, technique, anatomy, and physiology and repetitive strain injury. There has been growing evidence that the wheelchair-user interaction explains a substantial portion of the risk of developing a degenerative injury and on community participation. A noteworthy contribution of this work was the release of the clinical practice guideline, entitled, *Preservation of Upper Limb Function Following Spinal Cord Injury* in 2005.

Discussion—The SMART^{Wheel} has been used by other scientists in areas that were not originally envisioned to be applications. It has been used to support the design of tools for developing a trail mapping rating and description system. It has also supported the design of accessible pedestrian walkways standards, accessible playground surfaces, and to evaluate carpets for wheelchair accessibility. It is likely that there are more new areas of exploration to emerge. This article describes the evolution of the SMART^{Wheel} as new technologies became available and its applications in the field of wheelchair biomechanics and clinical service delivery.

Keywords

SMART^{Wheel}; Rehabilitation; Biomechanics; Medical Devices; Kinetics; Wheelchair

INTRODUCTION

Assistive technology for mobility enables people with disabilities to participate in home, employment, and social activities that might otherwise be inaccessible to them, and may also improve their quality of life (QOL). (Fuhrer et al. 2003; Scherer et al. 2005; Hubbard et al.

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2008) Numerous studies have concluded that reintegration into society and employment depend on access to appropriate and adequate assistive technology, such as wheelchairs. (Fuhrer et al. 2003; Scherer et al. 2005; Hubbard et al. 2008) The ultimate goal of providing mobility devices to people with disabilities is to promote full participation in society. (Schechtman et al. 2003) Wheelchair prescription is complex with thousands of choices and options. Theoretically, a higher quality or innovative wheelchair that is appropriately matched to the user and their unique needs will increase participation.

The initial work on developing the SMART$^{\text{Wheel}}$ came from the desire to better understand and improve the performance of wheelchair racing. The motivation largely came from a paucity of information about wheelchair racing biomechanics, which was limited by the tools available for measuring the forces and moments applied to the pushrim. Since the initial conceptualization, the SMART$^{\text{Wheel}}$ was intended to better understand the physiological and physical effects of wheelchair propulsion on the body. Over two decades later, the SMART$^{\text{Wheel}}$ has fulfilled most of the promise that was anticipated when the work began. This article describes the evolution of the SMART$^{\text{Wheel}}$ as new technologies became available and its applications in the field of wheelchair biomechanics and clinical service delivery.

BIRTH OF AN IDEA: 1986–1989

The first paper on the SMART$^{\text{Wheel}}$ appeared in 1989, and described the initial design and the basic mathematics behind the force and moment measurements. (Cooper & Cheda 1989) Prior to that time, much of the work focused on analysis, design, and fabrication. The first generation, SMART$^{\text{Wheel}}$ being designed for racing wheelchairs, incorporated a large ring with slots running along the axes of the spokes, see Figure 1. This was done to mount pushrims of various sizes as are often used by wheelchair racers. During this time-frame wheelchair racing athletes used pushrims as small as 28 cm and as large as 48 cm in diameter. The three-beam design was apparent in the very first generation and remains to this day. The sensing beams were originally square in cross-section with 0.6 cm on a side. The sensing beams were welded to the hub at one end and attached via rod-ends to the pushrim disk at the opposite end. This limited the force measurements that could be acquired. It would take a couple more generations until a full six-degree of freedom device was usable. The original prototype used strain gage bridges attached at the proximal end of the sensing beams. The beams were wired using coil wire, they were strain relieved and then cut several meters long. As the wheel rotated the wires twisted and had to be replaced after only a few uses. A general purpose differential amplifier and high-speed strip chart recorder were used to collect the force and moment signals during propulsion. Unfortunately, the forces and moments were greater than expected and the strain gages were damaged after only a few uses. The pushrim disks were also heavy, weighing several hundred grams, and not balanced which created considerable noise in the signals. However, a lot was learned that benefited fixture generations of the design, and some features such as the three-beam configuration still form the basis for the current SMART$^{\text{Wheel}}$ design.

MANUAL WHEELCHAIR SMART$^{\text{Wheel}}$ EMERGES: 1989–1991

Next the focus shifted from wheelchair racing dynamics, to the understanding of manual wheelchair propulsion. The change in focus was based on the importance of tackling the problem of the extremely high incidence of repetitive strain injuries among manual wheelchair users, and partially founded in the discovery that wheelchair racers did not appear to be at greater risk despite pushing many more miles per week than non-athletes. (Boninger et al. 1996) This provided an indication that the type and fit of the wheelchair to the user may be a substantial contributing factor to arm and joint injuries. Building upon the experience with the original SMART$^{\text{Wheel}}$, a new design was built around a plastic “mag” style wheel as shown in Figure 2. (Wantanabe et al. 1991) The disk was removed for a single pushrim design. The new beams were 1.9 cm square with an arrowhead shape at the proximal end in order to fit tightly in the notch of the intersection between two spokes and the central hub. A rectangular hole, when viewed from the sagittal plane, was machined into the beams under the strain gages in order to amplify the strain. A 0.6 cm thick round aluminum disk was used to tie the beams together near the hub to increase stiffness. A mercury slip ring was added to prevent the wires from twisting; however, due to cost constraints only two channels were used. In order to acquire a sufficient number of signals to decompose the strain gage bridge signals into forces and moments, we used analog frequency division multiplexing. Each bridge signal was assigned a unique carrier center frequency that was separated on the frequency band to prevent interference. These signals were then added, much like radio stations on the airwaves, and transmitted through the slip-ring. On the stationary side, the signals were decomposed and filtered using a custom circuit, and then sampled and stored on a computer. This proved to be very difficult and unreliable given the technology of the time. Besides the challenges of collecting data from a rotating wheel, the wheel had a tendency to deform under load, which caused problems for printed circuit board traces and solder joints.

Advances in micro-circuitry technology meant that we could reliability and reduce the number of chips required. The chip manufacturer Analog Devices (Norwood, Massachusetts, USA) introduced the 1B31AN strain gage bridge signal conditioning chip which greatly reduced the number of chips required and notably increased reliability. (Cooper et al. 1992) As before, power was brought to the on-wheel electronics circuit through a printed circuit board with circular traces and spring-loaded copper rods were used a contacts, see Figure 3. We were also able to purchase a 4-channel mercury slip ring, which allowed the outputs from the 1B31AN to be brought off the rotating wheel to a rack-mounted computer. This design only allowed us to measure the moment about the axle, but it provided the foundation for future success.

The next breakthrough came with the advances in the mechanical design. (Asato et al. 1993) The square beams were replaced with hardened ground steel beams that were 1.27 cm in diameter. These beams also served as the shaft for re-circulating linear bearings. The linear bearings were inserted into aluminum receivers that had precision rotary bearings in their distal end. Triangular steel plates were mounted at three points 120 degrees apart along the pushrim that were attached to the beam receivers with a shoulder bolt through each of the rotary bearings. Essentially, the pushrim floated on the three beams. This allowed each beam to practically be loaded in bending only, greatly reducing cross-talk. The proximal ends, near the hub, of the sensing-beams were inserted into a sturdy aluminum receiver in the shape of a triangle that fit tightly around the hub of the plastic “mag” wheel. It also proved to be a practical mechanical design that remains fundamentally unchanged. The electronics only required the addition of more of the strain-gage signal conditioning boards and a slip-ring with more channels. This design served the purpose well, and allowed for data collection to begin in earnest.

DATA COLLECTION BEGINS IN EARNEST: 1992–1993

With the availability of a reliable multi-axis SMART$^{\text{Wheel}}$, it was possible to begin the study of wheelchair propulsion biomechanics. (Asato et al. 1993; Robertson & Cooper 1993; Cooper et al. 1993a; Cooper et al. 1993b) Studies were still limited to a stationary wheelchair, but that could be accomplished using rollers or a treadmill. One of the design criteria from the onset for the SMART$^{\text{Wheel}}$ was to be able to mount it onto the personal wheelchairs of users. These early studies focused on understanding the characteristics of the force and moment curves, determining optimal filtering, errors in the calculation of the forces and moments, and in determining such features as the center of pressure. In parallel, we were developing models to be used for calculating the inverse kinematics of the upper limbs during manual wheelchair propulsion. This work went on for many years as it was important to ensure accurate and reliable data in order to understand actual wheelchair propulsion biomechanics in the least restrictive manner. During this time period, the desktop computer had advanced to the point where we could collect data on a personal computer. We created many software programs in Matlab (Natick, Massachusetts, USA) to condition and analyze the signals and accompanying data. (Cooper et al. 1993a; Cooper et al. 1993b; Ensminger et al. 1994)

SMART^{Wheel} GOES DIGITAL: 1994–1996

The next significant transformation of the SMART^{Wheel} came with the replacement of the analog circuitry with a digital circuit, as shown in Figure 4. (VanSickle et al. 1995) The electronics continued to rely on the AD1B31AN amplifier chips, which were designed into two pie-shaped boards with three of the strain-gage amplifier chips per board (one for each strain-gage full-bridge). Six full-bridges are necessary for discerning forces in the superior-inferior axis (y), anterior-posterior axis (x), and the medial-lateral axis (z), and the moments about each of these axes. In order to discern these forces and moments acting on the pushrim, the orientation of the beam must be known at each instance. This was accomplished using an optical encoder with full quadrature, which was interfaced to the microcontroller. The digital circuit was based upon the Motorola MC68HC11A1 microcontroller (Schaumberg, Illinois, USA). The outputs of each of the amplifier chips were connected to the analog to digital conversion lines on the microcontroller, and then transmitted to the RS-232 serial port of a personal computer through a mercury slip-ring.

By going from analog to digital directly on the SMART^{Wheel}, external electrical noise was reduced and a laptop could be used because the need for an analog to digital conversion board on the PC was no longer necessary. Prior to the digital SMART^{Wheel}, we had to transmit analog signals through wires up to 12 meters allowing the signals to be corrupted by noise, and then filtered which caused some signal attenuation. With clean and reliable signals such characteristics as dips at the beginning and ending of a stroke, representative of the inefficient coupling between the hand and pushrim, could be observed. The impact spike, the rapid rise in force on the pushrim when someone strikes it, could be investigated in greater depth. The cleaner data improved analysis of the net joint forces and moments. (Robertson et al. 1995a; Robertson et al. 1995b; Robertson et al. 1995c; Robertson et al. 1995d; Ensminger et al. 1995) This also allowed the feasibility of over-ground propulsion to be explored. During this time-frame, we also experimented with transmitting the serial RS-232 signal from the microcontroller board to a base station personal computer via an infrared (IR) transmitter-receiver pair. Although, this method worked, the IR signal would get disrupted (for example through sunlight or noise from an IR kinematics marker) and cause the connection to drop-out. As the hard-wired system was more reliable, and our studies were still largely focused on laboratory based biomechanics experiments, we and others continued to use the hard-wired version.

SMART^{Wheel} GOES COMMERCIAL: 2000 – 2001

With a reliable SMART^{Wheel} that was capable of providing all of the data required to conduct biomechanical analyses of manual wheelchair propulsion, our focus shifted towards data collection and analysis. However, the knowledge generated through using the SMART^{Wheels} created interest among research groups around the world. In the interest of advancing the understanding of manual wheelchair usage, and accelerating the pace of discovery so that people with disabilities would benefit from the science faster, we built SMART^{Wheel} for several other research teams around the world. We would only provide a SMART^{Whee}l to research groups that had local engineering support due to concern that we could become bogged down providing technical support. This approach proved manageable, and we learned a lot by communicating with other groups. This experience would serve us well, when the opportunity came to commercialize the SMART^{Wheel} and make it broadly available.

We began to realize that we were at cross-roads. We could continue along our path with a small group of people with access to SMART^{Wheels}, and able to conduct thorough biomechanical analyses of wheelchair propulsion, or transfer the SMART^{Wheel} to a commercial partner and see if the applications and knowledge base could grow. Fortunately, Ron and David Boninger, brothers of Dr. Michael Boninger my one-time post-doctoral fellow and long-time partner in research, approached Dr. Boninger to seek his advice about starting a business. This led to further discussions and an expression of interest to start a company to produce products languishing in the technology transfer pipe-line of academia or government that could help people with disabilities. Hence, Three Rivers Holdings, LLC (TRH; Phoenix, Arizona, USA) was born. Although, the SMART^{Wheel} had never been patented (the University of California at Santa Barbara, the Department of Veterans Affairs, and the California State University at Sacramento where the early intellectual property was developed all declined to pursue a patent), it was indentified as the first product that TRH would attempt to bring to market. The first step was to conduct a thorough review of the design of the SMART^{Wheel} that we and others had been using successfully for years, and determine what would be the features needed to make it commercially successful. Through this process, several key design criteria were identified: transition to a spoke wheel as the old nine-spoke “mag” wheel was no longer in production, create a robust casing for the electronics integrated with a new hub design, place shrouds over the strain-gage bridges, convert to wireless data transmission with on-wheel data back-up, easy installation on most wheelchairs, and user friendly software. Our laboratories collaborated with TRH on the next generation of the SMART^{Wheel} on the path to commercialization. A hub was designed and machined from a solid billet of aluminum. The hub became and remains the mechanical core of the SMART^{Wheel}, it served as the hub for the spokes to be laced to form a wheelchair wheel, it formed a foundation for the three sensing-beams to be secured to; it was the base to attach the circuit board and create part of the enclosure, it served to secure the optical encoder for recording wheel rotation, and it was the mate to the plastic enclosure. This first generation pre-production SMART^{Wheel} is shown in Figure 5. The axle was made with a wedge-nut to slide into a quick-release axle insert and then be tightened from the exterior. The cap to enclose the electronics was originally machined from a solid piece of nylon, but later when in production was injection molded. Bellows were placed over the strain gage-bridges. The electronics were reduced in size and transferred to a single multi-layer printed circuit board. A memory stick, like those used in digital cameras, was added to back-up data on the wheel. Wireless transmission was achieved by implementing IEEE 802 WiFi wireless local area network connectivity. Power was supplied by a lithium ion camcorder battery. Custom software was written in C++ with an easy to navigate graphical user interface. The first pre-production version was remarkable, as it provided reliable wireless connectivity, and easy to use software. It was clear that there was potential to greatly expand the people who could use a SMART^{Wheel} for either research or to enhance their clinical practice. (Boninger et al. 2004;Koontz et al. 2005;Collinger et al. 2008)

As is the case with many commercial products, feedback from customers leads to upgrades in future generations of the device. In the case of the SMART^{Wheel} over the years since first introduced, several areas have been improved. Most notably, the battery was relocated to be less vulnerable to impact (a result of use in natural environments), and there have been a number of WiFi and software upgrades, see Figure 6. A novel aspect in the marketing and usage of the SMART^{Wheel} has been the SMART^{Wheel} user group. When we conceived the concept of commercializing the SMART^{Wheel}, we envisioned creating a community of users that would share data that could be used to improve clinical services and expand research data sources. Therefore, anybody who purchases a SMART^{Wheel} is offered the opportunity to join the SMART^{Wheel} User’s Group (SWUG). The SWUG meets to share best practices, discuss experiences, and to design research studies. (Cowan et al. 2008) As a result of the work of the SWUG, the SMART^{Wheel} software includes a database of de-identified user data for comparison and patient education. This started the trend to collect data in clinical and community environments. (Koontz et al. 2007)

BROADER IMPACT OF THE SMART$^{\text{Wheel}}$: 1996–2009

Initially, little was known about wheelchair propulsion and the SMART$^{\text{Wheel}}$ transformed the nascent field of wheelchair propulsion biomechanics. First a whole host of characteristics were identified and analyzed, some of these include push-angle, peak forces and moments, time to peak, rate-of-rise, impact spike, point-of-force application, center-of-pressure, mean effective force, fraction of effective force, and braking moment. (Cooper et al. 1995; Cooper et al. 1996; Robertson et al. 1996; Cooper et al. 1997a; Cooper et al. 1997b; Boninger et al. 1997; Cooper et al. 1998; VanSickle et al. 1998)

Once stable and reliable metrics were established, the next natural step was to begin investigation of manual wheelchair set-up on propulsion biomechanics. This work led to the understanding the in most cases the pushrim forces are lowered as the rear axles are moved in the anterior direction; however, one must remain aware that rearward stability decreases and therefore a comfortable balance position for the user must be achieved. Further variables, such as seat height, seat width, and camber have also been investigated using the SMART$^{\text{Wheel}}$ as a tool. Much of this work laid the groundwork for the clinical use of the SMART$^{\text{Wheel}}$ to help determine whether the person is a good candidate for a manual wheelchair, to recommend the most appropriate wheelchair for a user, and how to best set-up the manual wheelchair for a particular user. (Boninger et al. 1999; Boninger et al. 2000; Boninger et al. 2001; Boninger et al. 2002; Koontz et al. 2002; Boninger et al. 2003; Boninger et al. 2005)

Although still an important area of clinical research, the SMART$^{\text{Wheel}}$ has been critical to the study of the relationship between the type of wheelchair, set-up, activity, technique, anatomy, and physiology and repetitive strain injury. It is well accepted that there is an alarmingly high incidence of carpal tunnel syndrome, and rotator cuff injuries among manual wheelchair users. Boninger et al. 2004; Koontz et al. 2005; Cowan et al. 2008; Mercer et al. 2006) Over the years, there has been growing evidence that the wheelchair-user interaction explains a substantial portion of the risk of developing a degenerative injury. By 2003 there was enough evidence for the Consortium for Spinal Cord Medicine to initiate work on a clinical practice guideline for preservation of upper limb function. One of the more noteworthy contributions of this work was the release of the clinical practice guidline *Preservation of Upper Limb Function Following Spinal Cord Injury* (Paralyzed Veterans of America, 2005) in 2005. The evidence continues to grow especially as larger multi-site studies are conducted. (Boninger et al. 2004; Koontz et al. 2005; Cowan et al. 2008; Mercer et al. 2006) In 2009, Max Mobility (Nashville, Tennessee, USA) introduced the OptiPush, a product derived from SMART$^{\text{Wheel}}$ research and development, further indicating the growing interest in wheelchair propulsion measurement technology.

CONCLUSION AND FUTURE WORK

The SMART$^{\text{Wheel}}$ has helped to provide the foundation for more thorough analyses of the biomechanics of wheelchair propulsion, to wheelchair ergonomics, and to understanding the mechanisms of repetitive strain injuries. It has gone from concept to commercial product for both research and clinical practice, and was essential to the support of a clinical practice guideline. While a number of important research contributions have been discovered through the use of the SMART $^{\text{Wheel}}$, there is still much to be investigated. Several of the significant milestones to date are presented in Figure 7. Wide accessibility and ease of use of SMARTWheel derived technologies has made it possible for a much larger and broader group of clinicians and scientists to contribute to the scientific knowledge base related to wheelchair usage and the interactions between policy, human, assistance, activity, technology and environment.

It is interesting to observe how the SMART$^{\text{Wheel}}$ has been used by other people in areas that were not originally envisioned to be applications. It has been used to support the design of tools for developing a trail mapping rating and description system. It has also supported the design of accessible pedestrian walkways standards, accessible playground surfaces, to assess sports performance, and to evaluate carpets for wheelchair accessibility. (Chesney & Axelson 1996; Longmuir et al. 2003; Cooper et al. 2004) It is likely that there are more new areas of exploration to come.

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Many people contributed to the SMART$^{\text{Wheel}}$ along the way, and their contributions great and small have helped to further our understanding of wheelchair propulsion biomechanics and the mechanisms of repetitive strain injury. Any list would be incomplete, but there are some people who made such important contributions to this work that not to recognize them would be a travesty. Some of those people who have made the greatest contributions to the design over the past two decades are: Archie Cheda, James F. Ster, III, David P. VanSickle, Michael L. Boninger, Kim Asato, Sean Shimada, Alicia Koontz, Ron Boninger, Chris Willems, David Boninger, Annette Vosse, Rick Robertson, Fred Baldini, Steve Albright, and Carmen DiGiovine.

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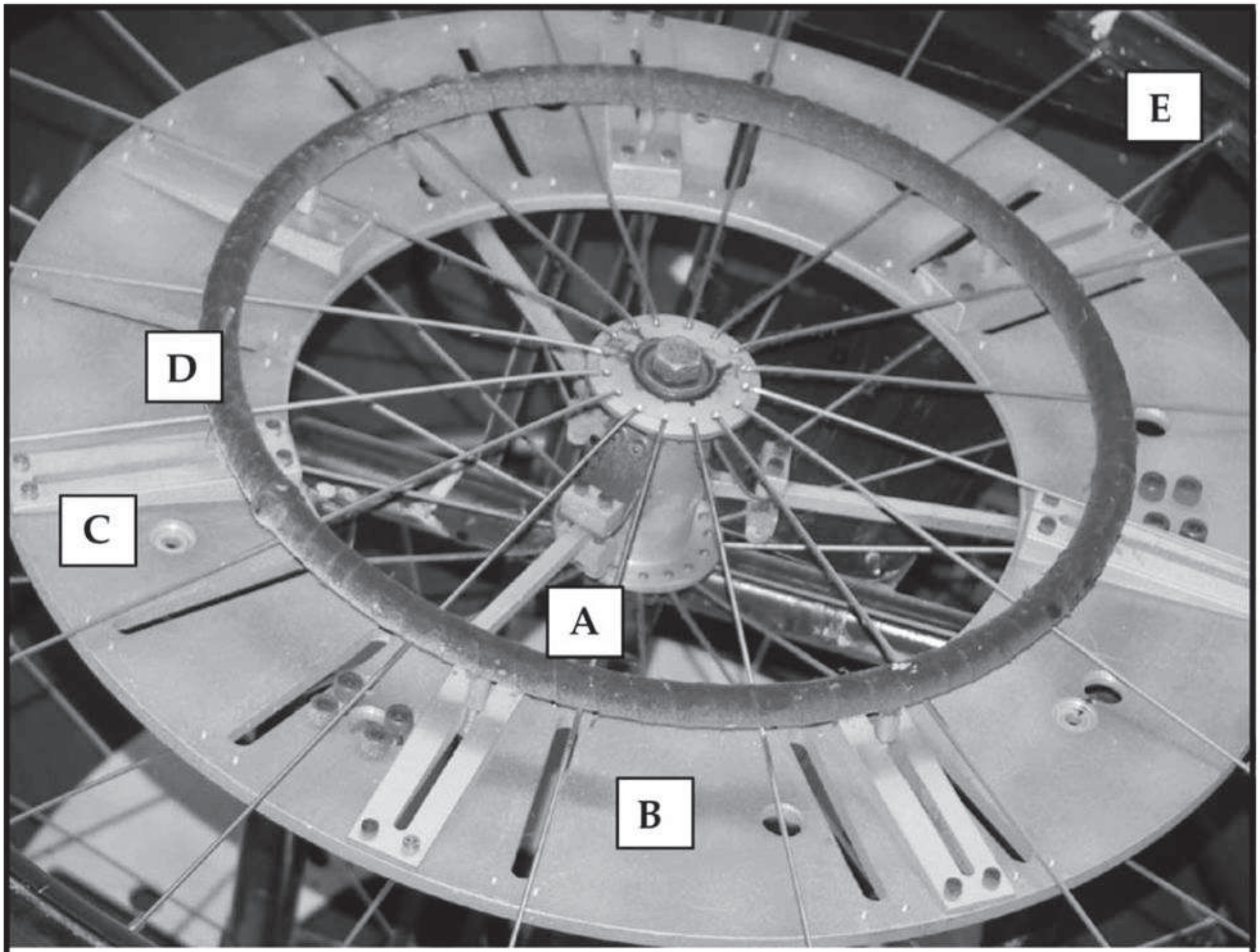


A. Sensing beam to record strain for measuring pushrim forces and moments.
B. Aluminum disk with slots to attach various diameter racing wheelchair pushrims.
C. Slotted wedge to match the angle of the spokes for attaching the pushrim.
D. Racing wheelchair pushrim.
E. Rim and tire of wheel.

Figure 1.
The first generation smart^{wheel} designed for racing wheelchairs.

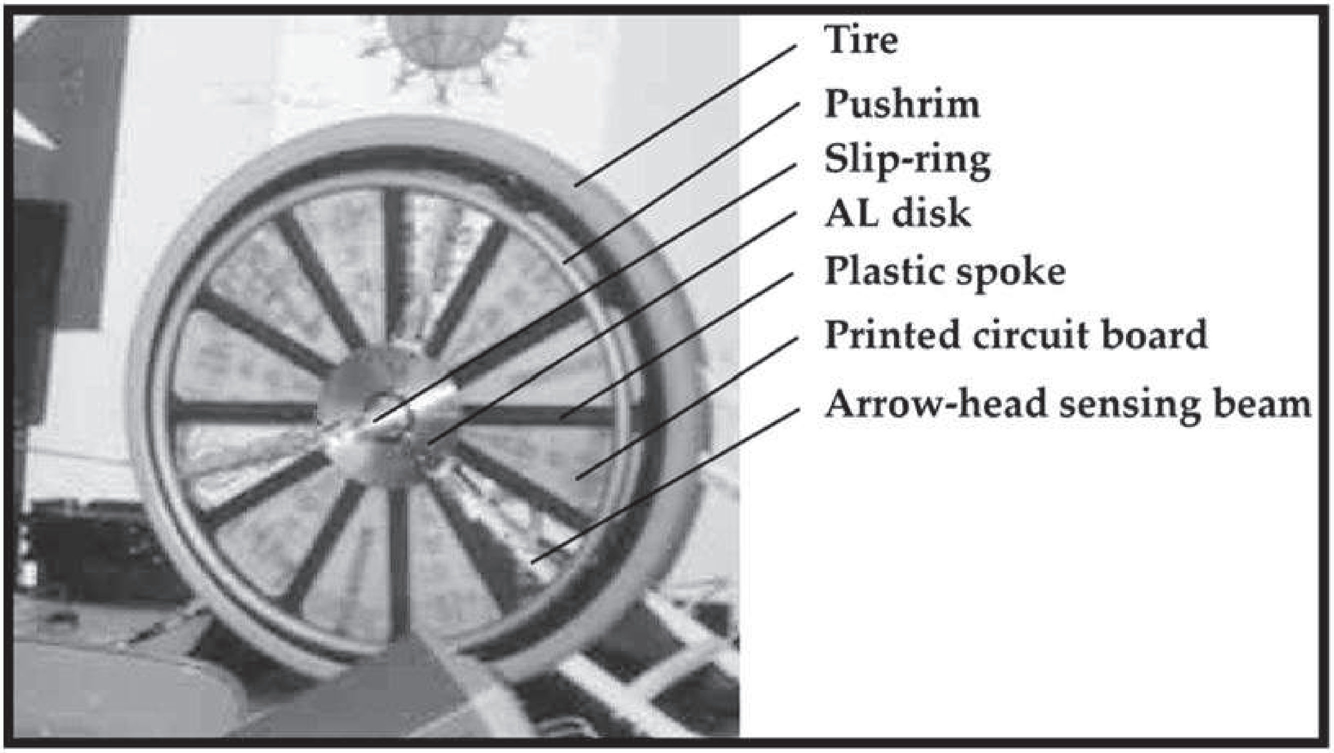
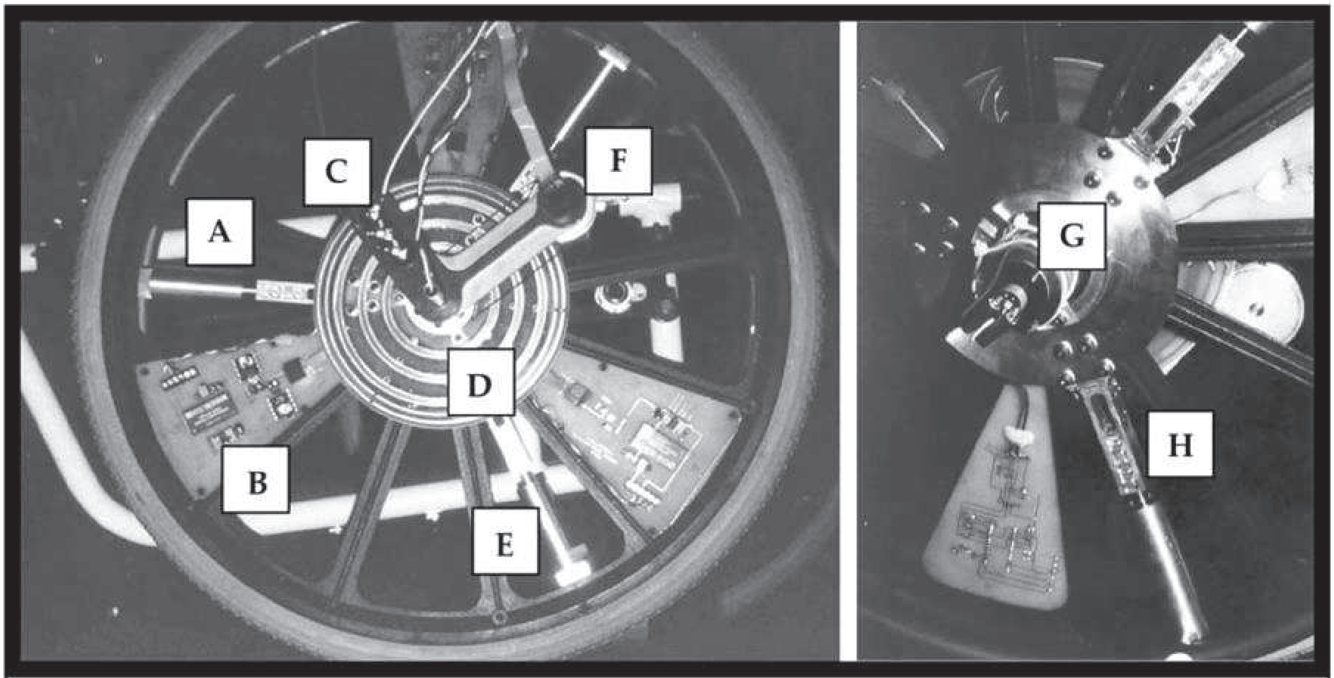
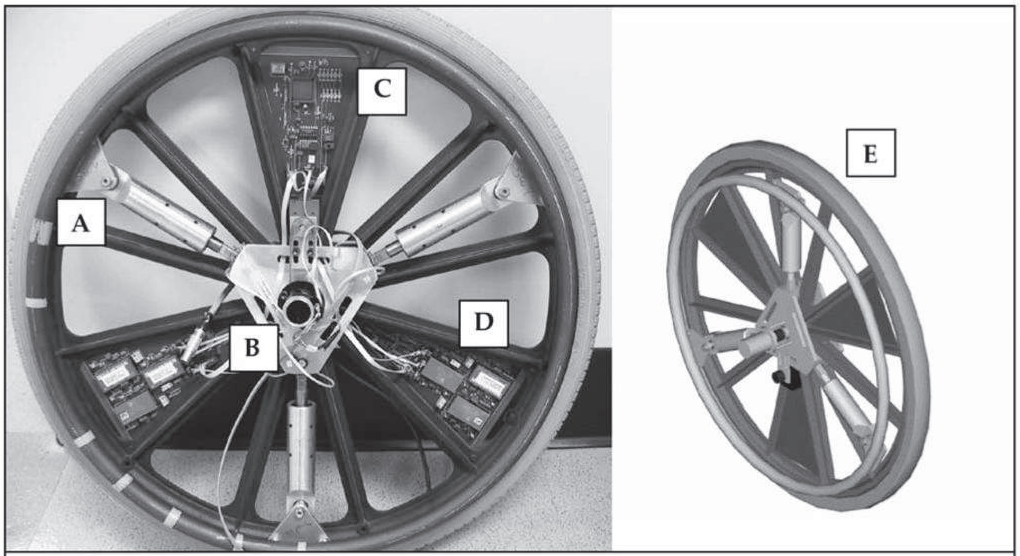


Figure 2.
Building upon the experience with the original smart^{wheel}, a new design was build around a plastic “mag” style wheel.



A. Aluminum linear bearing cylinder.
B. Amplifier and signal conditioning board with 1B31AN.
C. Power transmission spring-load Copper rods.
D. Circular printed circuit board for power transmission to wheel.
E. Plastic spoke.
F. Optical encoder for measuring rotation.
G. Mercury filled slip ring.
H. Strain gage bridge.

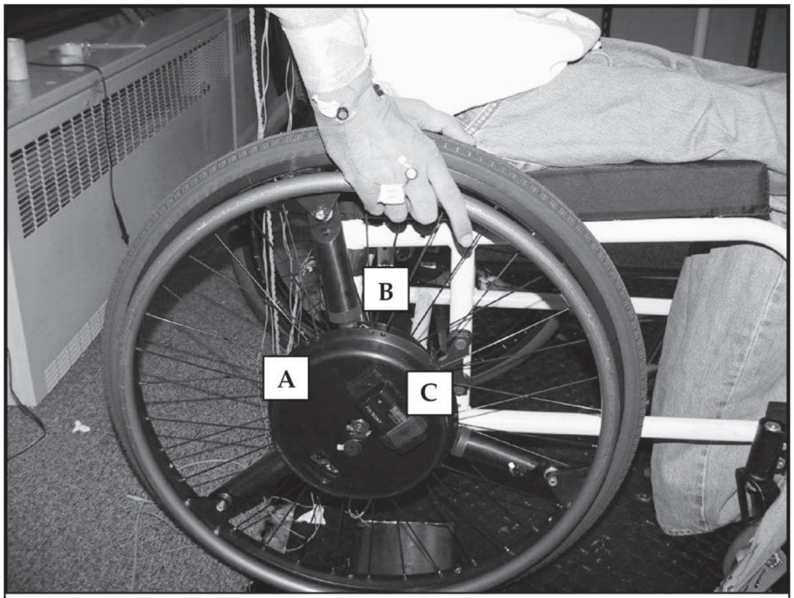
Figure 3.
Power was brought to the on-wheel electronics circuit through a printed circuit board with circular traces and spring-loaded copper rods were used a contacts, a 4-channel mercury slip ring allowed the outputs from the amplifier boards to be brought off the rotating wheel.



A. Triangle shaped pushrim attachment with rotary bearing to the inner side.
B. Aluminum receiver in the shape of a triangle that fits tightly around the hub.
C. Digital micro-controller printed circuit board.
D. Analog strain-gage signal conditioning printed circuit board.
E. Early computer aided design drawing.

Figure 4.

The next significant transformation of the smart^{wheel} came with the replacement of the analog circuitry with a digital circuit,



A. Hub with cap enclosing all electronics.
B. Sleeve to cover the strain-gage bridges.
C. Battery in its receiver.

Figure 5.

This first generation pre-production smart$^{\text{wheel}}$.

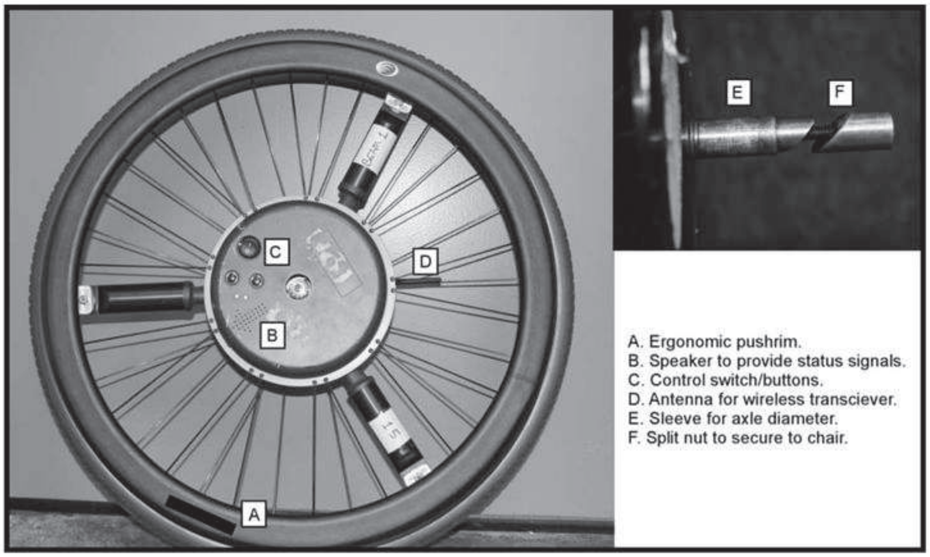


Figure 6.
The smart$^{\text{wheel}}$ over the years since first being introduced, several areas have been improved. Most notably, the battery was relocated to be less vulnerable to impact, and there have been a number of wifi and software upgrades.

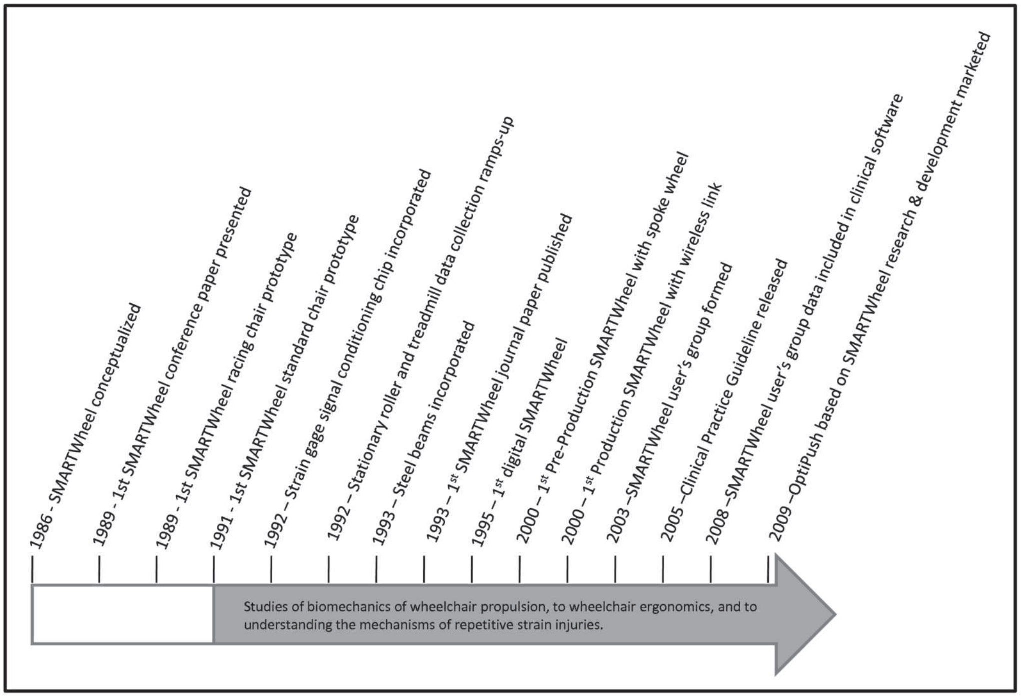


Figure 7.

Time courseof significant milestones to date.