Hand Rim Wheelchair Propulsion Training Using Biomechanical Real-Time Visual Feedback Based on Motor Learning Theory Principles

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Abstract

Background/Objective: As considerable progress has been made in laboratory-based assessment of manual wheelchair propulsion biomechanics, the necessity to translate this knowledge into new clinical tools and treatment programs becomes imperative. The objective of this study was to describe the development of a manual wheelchair propulsion training program aimed to promote the development of an efficient propulsion technique among long-term manual wheelchair users.

Methods: Motor learning theory principles were applied to the design of biomechanical feedback-based learning software, which allows for random discontinuous real-time visual presentation of key spatio-temporal and kinetic parameters. This software was used to train a long-term wheelchair user on a dynamometer during 3 low-intensity wheelchair propulsion training sessions over a 3-week period. Biomechanical measures were recorded with a SmartWheel during over ground propulsion on a 50-m level tile surface at baseline and 3 months after baseline.

Results: Training software was refined and administered to a participant who was able to improve his propulsion technique by increasing contact angle while simultaneously reducing stroke cadence, mean resultant force, peak and mean moment out of plane, and peak rate of rise of force applied to the pushrim after training.

Conclusions: The proposed propulsion training protocol may lead to favorable changes in manual wheelchair propulsion technique. These changes could limit or prevent upper limb injuries among manual wheelchair users. In addition, many of the motor learning theory-based techniques examined in this study could be applied to training individuals in various stages of rehabilitation to optimize propulsion early on.

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INTRODUCTION

Because of lower limb paralysis, individuals with spinal cord injury (SCI) rely extensively on their upper limbs for mobility and activities of daily living. Thus, any loss of upper limb function significantly affects mobility and independence (1–3). Some have gone so far as to suggest that damage to the upper limbs may be

functionally and economically equivalent to an SCI of a higher neurologic level (4). Unfortunately, upper limb pain is very common in manual wheelchair users, with carpal tunnel syndrome occurring in 49% to 73% of individuals (4–10) and rotator cuff tendinopathy and shoulder pain in 31% to 73% (4,8,11–14). Substantial ergonomics and propulsion biomechanics literature have identified specific biomechanical parameters associated with risk of injury to the upper limb (15–17). It is possible that appropriately training individuals to propel a wheelchair could result in a significant reduction in upper limb pain and injury. In an effort to reduce secondary injuries, the Consortium for Spinal Cord Medicine recently recommended that individuals minimize the frequency of propulsive strokes and the

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propulsive forces needed to manually propel a wheelchair (18). More specifically, wheelchair users should be encouraged to use low-frequency, long and smooth strokes during the propulsive phase while allowing the hand to drift down and back below the pushrim during the recovery phase (18). Unfortunately, many wheelchair users often receive little to no information from the rehabilitation professionals on how to safely propel a wheelchair, and no evidence-based training programs have yet been introduced into clinical practice.

Few recent studies have explored methods in which to improve manual wheelchair propulsion biomechanics (19–24). Two studies have proposed programs focusing primarily on upper limb strength training (24,25), whereas others have investigated simulated manual wheelchair propulsion training protocols completed on stationary ergometers at low intensities and durations with no feedback or with only visual velocity feedback (22,26,27). These studies have produced subtle but desirable changes on able-bodied subjects such as increased mechanical efficiency (ME), push time, contact angle, and decreased stroke frequency accompanied by little to no improvements in force application. To the best of our knowledge, only 2 research groups have implemented real-time visual feedback during wheelchair propulsion training at this time. de Groot et al (20,22) presented able-bodied subjects with real-time velocity and fraction of effective force (FEF) feedback and found trained subjects to exhibit higher FEF accompanied by significantly lower mechanical efficiency (20,22). Kotajarvi et al (23) presented FEF, velocity, and power output feedback to experienced wheelchair users and again found no improvements in force effectiveness, but did observe increased contact angle and decreased stroke frequency. FEF is the proportion of force at the hand rim that contributes to forward motion defined as F_t/F , where F_t is the tangential force obtained by dividing the measured wheel torque by the radius of the pushrim, and F is the resultant force. FEF is also considered a mechanical outcome measure that does not relate to ME consistently; therefore, higher FEF is not necessarily viewed as better from a physiologic or mechanical perspective (28). It has also been suggested that FEF does not change drastically with exercise or propulsion training because it is controlled largely by the geometry of the wheelchair–user interface, which is a closed chain from the shoulder down to where the hand grips the pushrim. ME is, however, an outcome measure shown to express improved performance during submaximal exercise and is sensitive to both changes in propulsion technique and wheelchair interface.

Although these studies have contributed substantially to the understanding of propulsion training, it is likely that further inspection is warranted, particularly in the area of visual feedback software design and presentation. It is possible that these studies may have had limited success because their visual feedback components were

not necessarily designed according to, or supported by, the principles of motor learning theory. Consequently, the question of how to best train an individual remains unclear. Motor learning theory indicates that the way in which visual feedback variables are selected and presented are most critical to skill acquisition, performance, and retention (29–32).

The purpose of this study is to describe the development of a submaximal training protocol that not only reflects propulsion biomechanics literature and clinical practice guidelines, but also attempts to optimize the effectiveness of visual feedback by incorporating elements of motor learning theory into its design. The proposed training protocol incorporates Biomechanical Feedback-Based Learning Software, with discontinuous real-time viewing of key spatio-temporal and kinetic parameters presented randomly while a participant propel his/her own wheelchair. The rationale of the training protocol parameters is described along with the technical characteristics of the software, which was specifically developed for manual wheelchair propulsion training. Preliminary results of one individual with SCI who completed the wheelchair propulsion training program are presented and briefly discussed.

METHODS

Biomechanical Feedback–Based Learning Software Development

The training program feedback screen presented (a) push angle, (b) cadence, and (c) velocity. A determination was also made to present these variables randomly and discontinuously (variables ordered randomly and appear and disappear during a trial). Variables would be presented 1 at a time (contact angle alone or frequency alone) and in combination (contact angle with frequency). A target velocity was also provided with these variables; however, no velocity was given during the self-selected speed condition. It is important to note that training and testing conditions requiring set target velocities were selected to be challenging, manageable, and distinct from one another. For example, the target velocity during training on the dynamometer was 2 m/s, whereas over ground testing occurred at 1.5 m/s to minimize learning effect between trials and also to accommodate a greater range of wheelchair users. Furthermore, these targets are close to normal adult walking speed and reportedly greater than the self-selected velocities of many active manual wheelchair users.

The proposed training software was originally programmed with flexibility in mind to support presentation of a number of continuous streaming variables. These variables include velocity (m/s), contact angle (degrees), stroke smoothness (peak/average force ratio), cadence (strokes/s), peak force (N), and average force (N). These variables were to be presented together, in real time, and continuously during propulsion. However, revisions were

made after a review of the literature on motor learning theory and based on suggestions from a coauthor, who is an expert in the field of motor learning theory and training methodologies. It was determined that the feedback portion of the training program presented an overwhelming number of continuous streaming variables that would be detrimental to learning. Motor learning literature indicates that too many interactive elements presented continuously can quickly exceed the capacity of a person's working memory, increasing cognitive load and thus making learning more difficult (33). Consequently, the number of feedback variables was reduced from 6 to 3, and their presentation was to occur discontinuously in random order and combination. The most challenging training scenario involved 3 variables at once; however, the majority of trials were limited to no more than 2 variables at a time in this exploratory study.

Motor Learning Theory Key Terminology

The items presented in 1 to 6 below are motor learning theory concepts applied to the design of the feedback training software.

1. External focus of attention: shifts a performer's attention away from his or her own movements and toward the effects of those movements that involve development of more automatic control processes (32,34).
2. Discontinuous variable presentation: variables presented intermittently; has been shown to improve learning (30,31,35).
3. Random practice: can enhance long-term retention and skill transfer (30,35,36).
4. Contextual interference: variable practice schedules occur in a random order and combination that improves learning (30,36,37).
5. Knowledge of Performance (KP): KP provides extrinsic, postresponse information about movement committing an action to memory (38).
6. Number of variables presented: too many variables presented in real time at once can degrade learning (33,35).

Variable Selection

Contact angle (degrees pushed during each propulsive phase), velocity (m/s), and cadence (strokes per second) were selected because they have been shown to have a strong association with the development of upper limb impairments. For example, studies have found a link between median nerve damage (the pathology behind carpal tunnel syndrome), forces applied to the handrims, and cadence (39,40). Studies by Boninger et al (41) provided longitudinal data that showed how a person propels his/her wheelchair can predict future changes in median nerve integrity. In addition, there is substantial ergonomics literature documenting the association between the frequency of a task and force exerted and risk

for injury at the shoulder and wrist (15–17). Stroke angle has been included so that, while reducing cadence, subjects do not impart large forces over a shorter stroke. By increasing stroke length, while assuming velocity is held constant, subjects will be doing an equivalent amount of work over a longer period of time. This may reduce the force exerted on the pushrim at a given speed. In addition, by focusing on cadence and push angle and not directly on the movement pattern of propulsion itself, external focus of attention is promoted, a motor learning technique shown to be beneficial in learning motor tasks. The advantage of focusing on the outcome of one's movements (external focus) is that the performer's attention is shifted away from his or her own movements and toward the effects of those movements. This type of learning involves development of more automatic control processes (31,34).

In addition, a decision was made to not use force feedback because our training program was submaximal and FEF tends to increase with higher work loads. It has also been suggested that increasing FEF may cause subjects to push with a higher percentage of force tangential to the pushrim, which could lead to unintended changes in biomechanics (20,21,23). Hence, the goal of this training program was to use cadence and push angle feedback to encourage subjects to take longer, less frequent strokes and to decrease force exerted at a given velocity, without causing unintended changes in force direction.

Presentation of Feedback Variables

Another question critical to the design of an effective training intervention relates to the way in which people learn and synthesize information. Careful thought had to be put into the design of practice schedules because they aimed to promote learning acquisition, retention, focus of attention, and transfer of motor skills. Given these considerations, the proposed training protocol has been programmed to provide discontinuous feedback with random ordered repeated training and rest periods (30,36,37). Motor learning literature suggests that continuous real-time feedback tends to decrease learning and retention of motor skills because the person can become dependent on that feedback as a substitute for his or her own error-detection and error-correction capabilities (29,35,38,41). Switching between tasks during practice provides the learner with better contrastive knowledge than the repetitive practice that occurs under a blocked or drill like order (42). Blocked practice sessions include only 1 aspect of a task, practicing it over and over until it is performed correctly, whereas random practices use multiple varied aspects of a task within a session. This contrast between tasks makes learning each task more distinctive and memorable, resulting in improved retention.

Random practice at different propulsion speeds can encourage the learner to compare and contrast the

Figure 1. Schematic representation of the contact angle which includes the initial (A) and final (B) hand contact with the pushrim during the propulsive phase of manual wheelchair propulsion.

methods and strategies used when propelling at a given speed (30). Shea and Morgan showed that ordering of motor skills during practice affects immediate performance and retention, whereas the manipulation of practice schedules creates an empirical phenomenon termed contextual interference (CI) (30). CI is a term that relates to the quality of learning experience that occurs during random vs blocked practice (30,36). CI is elevated during random practice because an individual must reform an action plan before executing the next motion or sequence. When CI is low, as is the case with blocked practice, an action plan suitable for an initial task remains in one's working memory ready for the next identical task requiring less effort and thought. The CI effect has often been considered a performance paradox because, whereas the increase in interference caused by random practice schedule diminishes initial acquisition, long-term retention and/or transfer performance are enhanced (30,35,36). Because the goal of this work was to maximize the long-term learning effects of training, practice schedules were administered randomly because this method has been shown to increase long-term skill retention better than blocked practice (30,35–37,42).

This training program has also been designed to provide a combination of reinforcement and feedback through KP (38,43). KP provides extrinsic, postresponse kinematic or kinetic information regarding aspects of movement otherwise difficult to perceive (38). In this context, KP, for example knowing push angle during wheelchair propulsion, directs a learner toward better performance of a goal-directed action like forward motion of a wheelchair. In contrast, practice without KP allows performance to drift away from the goal, weakening the representation of an action in memory.

Case Study

Our study involved 1 long-term manual wheelchair user (sex = male; age = 45.6 years; weight = 65.7 kg; height = 1.80 m) who sustained a complete T4 SCI more than 11 years ago. Subjective assessment and objective clinical examinations confirmed that this subject was not experiencing any active signs or symptoms of upper extremity impairments or any other condition that might alter his ability to manually propel his wheelchair during testing and training. The subject provided written informed consent before participation in this study as approved by the institutional review board.

Instrumentation

The participant's wheelchair was fitted bilaterally with 2 instrumented wheels (SmartWheel; Three Rivers Holdings, Mesa, AZ), whereas data were collected only from the side of the nondominant U/E (44). This instrumented wheel allows one to accurately record the 3 orthogonal components (x , y , and z) of the forces and moments applied directly to the wheelchair pushrim during propulsion within a local coordinate frame at a sampling frequency of 240 Hz (Figure 1). The instrumented wheel does not alter the feel or set up of a participant's own wheelchair, because it closely replicates usual wheel's size, position, and orientation when mounted. While propelling, key propulsion variables collected were streamed as real-time visual feedback and presented on a large monitor facing the participant. There was no perceivable delay between the actual action on the hand rim and the feedback received visually on the screen. In addition, the participant's wheelchair configuration was noted and maintained throughout the entire study, and the SmartWheels were equipped with solid tires eliminating the need to monitor tire pressure.

Figure 2. Schematic representation of realtime feedback variable presentation during training. Sixty-second rest periods followed each 55-second propulsion period and 2 minutes of rest occurred after each block of training. Within a propulsion period a subject was given 5 seconds to acclimate and then received visual feedback for 10 seconds, no feedback for 15 seconds, feedback for 10 seconds, and no feedback for the remaining 15 seconds. A training block was considered presentation of all combinations of variables with a target velocity or at a selected speed.

During training, the participant's wheelchair was positioned over a custom-built computer-controlled wheelchair dynamometer anchored to the floor using a 4-point tie-down system. The dynamometer used for training was comprised of an independent double drum system. The target velocity presented was $2 \text{ m/s} \pm 0.25 \text{ m/s}$ in the value of a bar range reportedly close to normal adult walking speed (45). The study was designed to occur at a low intensity while maintaining speeds and rolling resistance typically encountered during daily propulsion. The rolling resistance of the dynamometer used was fixed at 14.2 N, reportedly just under that of rolling on low pile carpeting (46,47).

Wheelchair Propulsion Assessment

Biomechanical assessment of over-ground manual wheelchair propulsion was performed on enrollment and 3 months after enrollment. During these assessments, the subject was instructed to manually propel his wheelchair at a self-selected speed (task 1) and at a predetermined speed of 1.5 m/s (task 2), respectively,

over a 50-m distance on an unobstructed, in-door, level tile surface (width = 3 m). To ensure that the predetermined speed of 1.5 m/s was maintained during task 2, the subject was instructed to follow a power wheelchair traveling at this preset speed (48). Spatio-temporal and kinetic data were recorded during these over-ground assessments. Over-ground wheelchair propulsion was favored over dynamometer testing because it is thought to be more representative of routine wheelchair propulsion observed in daily life.

Wheelchair Propulsion Training Protocol

The subject visited the laboratory 4 times over a 3-month period. The first 3 visits included real-time feedback training on the dynamometer followed by testing on the dynamometer and on an over-ground course. Training occurred on V1, V2 (10 days after V1), and V3 (10 days after V2). The fourth visit occurred 3 months after V1 and involved only testing on the dynamometer and over ground. All training occurred at low intensities, thus isolating effects of technique learning rather than fitness

Figure 3. An example of an actual real-time screen display where all feedback variables are presented. Speed is presented in the first 5 seconds to help the subject acclimate and reach the steady-state target speed and then all of the variables are visible for 10 seconds and disappear for 15 seconds while the subject continues propulsion. The bars on the left of each block have a green target area in the middle; the red upper range indicates above target, while the lower yellow region indicates below target. The blue bars to the right of the target are the wheelchair users' real-time data streamed from the instrumented wheel at 240 Hz.

training or physiologic adaptation. The longest period of time spent in propulsion without a break was 55 seconds. During that 55-second period, the participant would propel continuously while receiving visual feedback (contact angle, stroke frequency, velocity) that would appear and disappear during the trial (Figure 2). All combinations of variables presented equated to 12 minutes of active propulsion with a total rest time of 14 minutes. A target velocity (self-selected speed and 2 m/s) was highlighted in a range of bright colors against which real velocity was plotted. For the stroke frequency and contact angle, real values were directly displayed on the screen (Figure 3). Before training, the subject was instructed to minimize cadence and maximize contact angle while maintaining velocity.

Outcome Measures and Data Analysis

Key spatio-temporal and kinetic parameters were computed during the propulsive phase of 5 consecutive stroke cycles during manual wheelchair propulsion after a near-constant velocity (steady state) was achieved. The start ($F_{\text{resultant}} > 5 \text{ N}$) and end ($F_{\text{resultant}} < 5 \text{ N}$) of the push phase of each stroke were automatically selected using a customized Matlab program (The Mathworks, Natick, MA). Spatio-temporal outcomes included the mean propulsion velocity (m/s), mean stroke cadence (number of stroke/s), mean absolute push time (s), and mean contact angle per stroke (degrees). Kinetic outcomes included the peak and mean resultant forces applied to the hand rim ($F_{\text{resultant}}$), the peak and mean moments out of the plane of the wheel (M_p) applied by the hand, and the rate of rise of force ($\text{ROR}_{\text{Force}}$).

For these outcome measures, changes were observed between the first and final visit 3 months later to document the effects of the training program on 1 individual.

RESULTS

As seen in Figure 4, the subject increased contact angle while simultaneously reducing stroke cadence, mean resultant force, and peak rate of rise of force applied to the pushrim at both self-selected and predetermined velocities. At a target velocity, contact angle increased from 107.3 ± 10.5 to 120.2 ± 15.3 degrees, whereas decreases were seen in stroke frequency (1.2 ± 0.5 – 0.5 ± 0.05 strokes/s), mean resultant force (59.9 ± 4.5 – $45.6 \pm 7.1 \text{ N}$), and peak rate of rise of force ($2,250.1 \pm 315.0$ – $1,584.4 \pm 1,012.3 \text{ N/s}$). At a self-selected speed, contact angle increased from 94.3 ± 18.9 to 109.7 ± 12.6 degrees, whereas decreases were seen in stroke frequency (1.0 ± 0.6 – 0.49 ± 0.04 strokes/s), mean resultant force (47.1 ± 12.3 – $41.6 \pm 5.4 \text{ N}$), and peak rate of rise of force ($1,623.4 \pm 974.4$ – $895.6 \pm 227.5 \text{ N/s}$). A small change in self-selected speed was observed before to after training (1.52 – 1.45 m/s). With increased velocity, a higher power was seen in force directed tangentially to the hand rim (31.5 – 47.9 W ; Figure 4).

DISCUSSION

Manual wheelchair propulsion can be an intense activity requiring the application of large forces to the pushrim repetitively over time. The risk of developing secondary upper limb impairments justifies the need for interventions that can minimize the progression of these potentially debilitating conditions. This article presents the rationale supporting the proposed training protocol along with an overview of its technical characteristics.

The results of this exploratory study confirm that favorable changes can be observed after completing a submaximal propulsion training protocol based on contact angle and stroke frequency visual feedback. In fact, the case subject studied in this study was a long-

Figure 4. Summary of the kinetic and spatio-temporal outcomes measured before and after training during manual wheelchair propulsion at a predetermined (1.5 m/s) and at a self-selected speeds. Solid bars correspond to mean values measured at baseline, before training, whereas dotted bars represent mean values reached 3 months after baseline after 3 training sessions.

term wheelchair user presenting with well-defined propulsion biomechanics; however, training still produced substantial changes. The subject's mean stroke cadence decreased with an increase in mean contact angle. In addition, the mean resultant force, mean moments out of the plane of the wheel, and rate of rise of resultant force were also reduced. All of these changes occurred while velocity remained constant, and all stroke improvements occurred and persisted 3 months after baseline assessment. In the self-selected speed condition, a small drop in velocity was observed; however, the subject reduced total average force while generating more power, taking fewer strokes, and increasing contact angle. We believe that these values may indicate improved technique.

It was an aim of this project to establish a clinically useful tool geared toward injury prevention rather than purely maximizing gross mechanical efficiency. Direct force feedback like FEF was eliminated as a training variable because the literature indicates that it does not

always relate to ME consistently and can cause radical and unsafe alteration of their propulsion technique (23). In addition, it is evident that propulsion on a dynamometer does not always translate to over ground where an individual must incorporate chair handling skills and use visual and environmental cues during propulsion. However, this study showed that the participant's propulsion biomechanics could be improved over ground after training on a dynamometer alone. As more subjects complete this training protocol, the findings will help verify the programs effectiveness, generalizability, and the extent to which it can serve as a safe and practical clinical tool.

Although careful thought was put into the program's design to illicit improved propulsion biomechanics, inherent limitations exist. It is evident that shifts in mechanical efficiency can take place because of physiologic adaptations or as a consequence of improved propulsion technique (20). As a result of training, both physiologic adaptations and learning responses (ie, an

improved propulsion technique) can take place as well. If one is to isolate changes in propulsion technique and ME, physiologic adaptations as a consequence of training should be excluded. Therefore, a learning protocol needs to occur at a low intensity, duration, and frequency (20). For example, the dosing and timing of practice schedules in this protocol were intended to be submaximal and spaced out to minimize physiologic adaptations. It is apparent, however, that some degree of unintended physiologic adaption and motor learning may have occurred. It is likely that, even a control subject propelling without training or receiving only velocity feedback, could exhibit natural learning and some degree of physiologic adaptation.

The current protocol requires at least 1 instrumented wheel, a dynamometer, and a computer to support the software that could be perceived as disadvantageous. However, the cost savings resulting from a potential reduction in secondary upper limb impairments could easily offset initial expenses and should not be overlooked. It is also important to consider the possibility that a successful training program could be carried out based on the principles of this study using less equipment and technology. For example, with only verbal feedback provided by a therapist and 1 instrumented wheel, it may be possible to effectively measure and train an individual's stroke technique over time. In fact, clinicians without access to an instrumented wheel could still teach propulsion using verbal or auditory feedback based on the motor learning principles and clinical practice guidelines presented in this study. A client could be told to use low cadence, and long smooth strokes, with intermittent verbal instruction, over random ordered practice surfaces like carpet, ramp, and tile. Again, consistent with motor learning theory, a client could benefit from additional feedback, which places emphasis on the effects of their movements like number of strokes taken, speed, and stroke length rather than movement pattern. The use of a low-cost video camera could also be used to record propulsion technique, which could assist both the instructor and client throughout the learning process.

How far subjects are from propelling with ideal technique will vary from individual to individual. However, the literature has reported that a large range of cadences and push angles often occurs within representative populations of wheelchair users (49–51). More specifically, a study completed comparing the propulsion techniques of long-term wheelchair users found that, at a given speed, the average group cadence varied from 1.1 to 1.6 stroke/s, and the push angle varied from 102 to 134 degrees (49). The significant group variability indicates that there is considerable room for improvement. In addition, gross ME during propulsion has been shown to rarely surpass 11%, which also suggests improvements in technique may be attainable (52). These findings may have meaningful and clinically

significant implications because propulsion occurring inefficiently may place a person at significant risk for developing upper extremity pain and injury. Because wheelchair propulsion involves impacting the pushrim thousands of times per day and clearly exceeds what the ergonomics literature considers to be a high force, high repetition task, any improvements could have an impact on the development of upper extremity pain and injury.

This case study was ultimately a starting point and could eventually serve as a new teaching approach for rehabilitation practitioners. Additional research needs to be conducted with a greater number of long-term manual wheelchair users in a randomized design with a control group before the beneficial effects of training can be ascertained. The next logical step may be to develop a randomized clinical trial to verify whether this program prevents, or limits, the development of secondary upper limb neuro-musculoskeletal impairments over time.

CONCLUSION

This study translates key principles of motor learning theory into visual feedback learning software presenting customized spatio-temporal and kinetic variables known to be critical to the development of efficient propulsion techniques. Preliminary results indicate that clinically relevant changes can be expected 3 months from baseline after only 3 low-intensity wheelchair propulsion training sessions completed over a 20-day period by a long-term manual wheelchair user with SCI.

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Ernest H.J. Bors, MD (1900–1990) emigrated from Europe to the US in 1939 and became a citizen. At the outbreak of World War II, he joined the Army Medical Corps and served as a surgeon. Motivated by the needs of veterans with spinal cord injury (SCI), he became the foremost expert on neurourology in SCI. Dr Bors developed a holistic multidisciplinary approach that formed the foundation for modern SCI centers in the US. During a career of caring for more than 2,500 veterans with serious disabilities, he conducted groundbreaking research at the bedside and shared his findings in more than 140 scientific papers. His text, co-authored by Estin Comarr, MD, *Neurological Urology, Physiology of Micturition, Its Neurological Disorders and Sequelae*, remains the authoritative text in this field.