The case for active safety for power wheelchair users with spinal cord injury.

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INTRODUCTION

Scope of the problem: Complex Rehab Power Wheelchairs (PWC) are critically important assistive devices for Veterans with spinal cord injury (SCI) which provide mobility independence and increase quality of life. To do this, they must be compact and agile for use in the community. Even optimally configured PWC’s can prove dangerous during daily operation and lower extremity (LE) injuries can occur when the feet of users who cannot feel, see or easily reposition their LE are mispositioned on the footplates. Constant attention to foot position increases cognitive and visual load, which can distract from wheelchair operation [1]. Paralysis limits users’ ability to reposition their feet and lower limbs on their PWC footplate, potentially requiring assistance from caregivers, and systemic consequences such as spasticity, contractures, osteoporosis, and tissue health increase LE injury risk.

The impact of injuries due to inadvertent lower extremity displacement (ILED) nationwide is masked by deficiencies in our medical reporting systems which prevent extraction of incidence data. Kirby [2] summarized wheelchair-related adverse FDA reports in the SCI population, the most common being fractures, lacerations, and contusions/abrasions. Morse et al. [3] found that almost half (47.5%) of a cohort with chronic SCI sustained tibia/fibula fractures requiring re-hospitalization, with 6.7% of these due to catching a lower extremity on a doorframe during wheelchair operation. These hospitalizations resulted in long stays, medical complications and often discharge to a nursing facility. In a three-year survey, Chen et al. [4] reported 54.7% of wheelchair users had at least one accident and 33% of PWC users reported accidental contact with obstacles. Additionally, striking an object accounted for 4.8% of the injuries to wheelchair users treated in US emergency departments reported in a survey of the National Electronic Injury Surveillance System between 2002 & 2003 [5].

Wheelchair Design Contribution: There are several factors in PWC design which have an impact on risk of foot and lower limb injury. The optimal specifications for a PWC are achieved by considering the user’s cognitive, physical condition and living space to select a configuration that meets as many user needs as possible with the least number of concessions. However, there is no such thing as a perfect wheelchair. The following features may increase risk of lower limb injuries, despite providing improved maneuverability in tight spaces.

Footplate design impact on foot positioning and safety. Many modern PWC models utilize center-mount legrests to shorten PWC length and create tighter turning radii to improve maneuverability. The center-mount footplates hold the feet closer together than the previous common swing-away legrests due to positioning relative to the wheels. Front wheel-drive PWCs with center-mount footplates provide the best positioning and ergonomic functionality because the wider spacing of the front wheels allows maximal footplate surface area for foot placement and containment with relatively minimal risk for the feet to come off the side of the footplate. However, mid-wheel drive PWCs are more commonly prescribed because they have the smallest turning radius, which is ideal for negotiating tight spaces. The footplate width must be narrow on these PWC because the front casters can rotate to be only 11-12” apart during turns. If designed with wider footplates to optimize foot positioning, the legrests must angle upward to clear the front casters, increasing effective chair length, its turning radius, and risk that the user’s feet contact the environment during tight turns. The alternative is a narrower footplate which fits between the front casters and reduces chair length but provides less foot support leaving users’ feet prone to coming off the footplates. Additionally, most footplate designs do not extend the full length of the average adult male foot; and in close quarters maneuvers, toe contact with adjacent objects can pivot the foot without the user’s knowledge. Center-mounting posts require a flat foot position on the footplate and inversion and eversion cannot be customized for joint contractures and spasticity (Figure 1).

Center-mount footplates provide scant lateral support to stop paretic thighs from externally rotating at the hip. Lateral thigh supports may fix this problem, but may not be available depending on payor source [6]. Some PWCs lack fore and aft calf-pad adjustability to support the lower leg, increasing leg position instability if the feet come off the footplate.

Weight-shifting in tilt-and-recline PWC: Positioning in PWCs with power tilt and recline provides pressure relief for the user who cannot perform

Figure 1: Center-mount footplate demonstrating foot positioning issues.

Figure 2: Tilt and center-mount leg post length
Due to the scarcity of data to elucidate specific mechanisms of injury from ILED on the footplate during wheelchair mobility [2,9], our team analyzed MAUDE database reports of wheelchair mobility-related injuries due to ILED from WC footplates submitted between 2014 – 2018 to identify injury types and evaluate MAUDE data quality.
The database was searched for Product Class “Wheelchair, Powered” or "Wheelchair, Mechanical (Manual)" and the Event Type “Injury.” Report narratives were reviewed and those for wheelchair mobility-related injuries due to ILED on the footplate were extracted for further analysis. The study was exempt from IRB review.

Twenty-nine of 1075 injuries related to ILED on the footplate occurred during wheelchair mobility. All were classified as “adverse events,” and only three were also classified as “product problem reports.” Most occurred in power wheelchairs. The most common injuries reported (absolute number, percentage) were single fractures (10, 34.5%), wounds/cuts/infections (5, 17.2%), multiple fractures (5, 13.8%), amputations (2, 6.9%) and multiple fractures with wounds (1, 3.5%). In 24% of injuries, the injury details were unknown. In ~59% of mechanism reports, the foot slipped off the footplate unknown to the end user, followed by catching the feet between the footplate and an object (20.7%), running the feet into objects (10.3%), feet hanging over the footplate (6.9%), and the feet “banging” on the footplate (3.5%). The exact mechanism of ILED was often ambiguous in the narrative.

Mandatory manufacturer reports appeared to exhibit reporting bias indicating “end user error” as the cause without considering how user impairments in the context of product’s use and the environment may limit user ability to comply with manufacturer recommendations. Example comments include:

“Investigation revealed that the root cause of this failure mode is "improper use: device interface"…"It was reported that the patient was improperly positioned in the wheelchair leaving his right leg hanging off the side of the seat which increases the risk of potential injury if struck by an external object."

“The patient was not” …” utilizing a ramp with a 14.7 degree slope.”

"...avoid uneven or unstable surfaces such as potholes, broken pavement, grass, gravel, and sand.”

Such reports presume a choice regarding the environments and inclines being traversed, as well as full control over body positioning, which are not the case for PWC users with SCI. There are significant limitations to the MAUDE database passive surveillance system. Reports are voluntary for consumers and healthcare providers, and mandatory but not enforced for manufacturers. The dearth of reports relative to our known incidents raise concerns about compliance and awareness of this etiology of LE injuries. Despite SCI complications such as osteoporosis, fractures, wounds and amputations should not be expected outcomes of wheeled mobility use. In order to avoid harm to patients, solutions to improve wheelchair safety are needed. Product technology has the promise to help PWC user, their caregivers and families overcome the problem of ILED-related LE injuries.

**EMERGING SOLUTIONS**

Active safety measures to improve automobile control and prevent crashes now common in late model automobiles include blind spot warning, forward collision warning with automated emergency braking, anti-lock braking, lane keeping assist, and pedestrian alerts [11,12]. Autonomous navigation and auto stopping are commercially deployed in mobile robots, such as pharmacy delivery systems in hospitals [13]. However, “smart” wheelchairs utilizing sensors to achieve active safety for PWC users are still not a commercial reality today [14].

Our interdisciplinary team created a low-cost, PCT-pending [15], smart wireless footplate pressure and position sensor (FoPPS) [16] (**Figure 4**) which monitors foot position and detects changes in force distribution and proximity due to inadvertent foot mispositioning during PWC use with a goal of addressing the unmet clinical need for real-time prevention of lower limb injuries during PWC use. The innovative FoPPS footplate overlay encapsulates 23 force-sensing resistors (FSR) and 14 infrared (IR) distance sensors in an array designed to fit precisely within each footplate borders. The sensors transmit foot pressure and position data at 10 Hz with Bluetooth Low Energy radio to an iOS application (**Figure 5**) which was developed to notify users of vulnerable foot position. The FoPPS system is now ready for testing by PWC users with SCI in the typical conditions and activities of daily living (ADL), e.g. driving over rough terrain or pressure relief using tilt-in-space which can cause ILED from the footplates.

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**Figure 4:** FoPPS System 2.4 and 2.3 footplates
A. FoPPS 2.4 - Left Footplate (Simpact 85A, urethane encapsulation, custom tint-able)
B. FoPPS 2.3 - Right Footplate (Econ 80, 80A urethane encapsulation)
C. FSR’s
D. IR Sensors
E. Left/Right Interconnect cable
F. Teensy and HM-10 Bluetooth module
G. USB battery
H. Closed electronics container
I. Interconnection pins for functional testing and calibration during prototyping.

**Figure 5:** FoPPS iOS Application Interface Options
Safe wheelchair use currently depends on educating users on safe operation technique and consistent implementation of what was taught. This requires the user to have intact vision, cognition and impulse control [17,18]. Development of smart footplate position sensing and feedback will serve as the basis for developing active safety interventions (Figure 6) to address the unmet clinical need for real-time prevention of lower limb injuries during PWC use. Additionally, widespread use of the smart wireless Footplate Pressure and Positioning Sensor (FoPPS) system will help determine the incidence of such lower limb injuries and near misses. Active safety interventions should be developed and tested to improve PWC safety.

REFERENCES


