Concept Proposal for a Detachable Exoskeleton-Wheelchair to Improve Mobility and Health

Jaimie F. Borisoff, Johanne Mattie, Vince Rafer
Rehabilitation Engineering Design Laboratory
British Columbia Institute of Technology
Burnaby, BC, Canada
Jaimie_Borisoff@bcit.ca

***Abstract*— Wheelchair use has consequences to quality of life in at least two areas: 1) health issues such as pressure sores and chronic overuse injury; and 2) access problems due to the inaccessible nature of the built and natural environments that are most amenable to upright postures. Even with these concerns, wheelchairs are still the best form of mobility for many people (e.g. they are relatively easy to transfer into and propel). However, wheelchairs are simply not transformative, i.e. they do not allow a person with a disability to attain a level of mobility performance that approaches that of their non-disabled peers, nor do they typically allow for face to face interactions and full participation in the community. Wheelchairs also do not typically support ongoing therapeutic benefits for the user. To address the inadequacy of existing wheelchairs, we are merging two evolving technologies into a coherent new mobility device. The first is dynamic wheeled mobility, which adds significant functionality to conventional wheelchairs through the use of on-the-fly adjustable positioning. The second is powered walking exoskeletons, which enable highly desired standing and walking functions, as well as therapeutic benefits associated with rehabilitation gait training. Unfortunately, exoskeletons have significant usability concerns such as slow speed, limited range, potential to cause skin issues, and difficult transfers. A new concept of docking a detachable exoskeleton to a wheeled frame has been developed to address these issues. The design goal is a single mobility device that not only optimizes daily activities (i.e. wheelchair seating and propulsion with dynamic positioning), but also serves as an easy-to-use rehabilitation tool for therapeutic benefits (i.e. a detachable powered exoskeleton for walking sojourns). This has significant potential benefits for the lives of people with mobility impairments.**

Keywords—wheelchair; exoskeleton; dynamic seating; mobility; walking; wheeled mobility

I. Introduction

Built and natural environments are often inaccessible to people with disabilities and the aging population. At best, mobility and opportunities for full community participation are limited following the onset of disability. This is understandable when we consider that our world is designed and built primarily for upright walking and standing, while a common mobility aid for people with various disabilities is the wheelchair. The inaccessibility of society is an issue both in terms of simply moving from place to place, but also in terms of full interaction with other people throughout normal daily activities (e.g. standing face to face, reaching shelves, etc.). Nevertheless, modern wheelchairs are a widespread and very successful assistive technology (AT) for people with disabilities, with evolved designs that enable activities of daily living and promote some participation in the community [1, 2]. Unfortunately, long-term use is associated with a myriad of health and quality of life (QoL) issues [1] - clearly the reliance on current wheelchair technology is limiting. Wheelchairs today are simply not transformative, that is, they do not enable a person with a disability to attain a level of mobility performance approaching that of their non-disabled peers [3, 4]. Most wheelchairs today are also not therapeutic, that is, they do not improve the underlying condition, health, or functional recovery of the individual. A worthwhile goal in rehabilitation engineering research related to mobility is to address the issues related to the inadequacy of existing wheelchairs by striving to create technology that can optimize daily activities, and yet also serves as a rehabilitation tool offering potential therapeutic benefits.

Our approach is to combine two evolving mobility concepts into a coherent and completely new device suitable for all day use by people with mobility impairments. The first concept is ***dynamic wheeled mobility***. Modern conventional wheelchairs are well accepted and practical. They are relatively easy to transfer into and out of, and facilitate normal activities of daily living (e.g. transfers to bed, shower, and toilet), provide adequate stability while performing tasks, are easy to propel indoors and in the community, and efficiently move people from place to place. However, long-term wheelchair use (and static sitting) is associated with a myriad of issues including: pain and discomfort; pressure-related skin breakdown; joint immobility and contractures; spasticity; and musculoskeletal issues associated with mobility via chronic arm propulsion [1]. The use of dynamic seating, similar to that employed in conventional adjustable seating (e.g. modern office chairs), may mitigate some of these issues [5-8]. The concept of dynamic seating, as defined here, refers to a user's ability to easily and quickly (i.e. in real-time while sitting in the chair) adjust their seating position independently during normal wheelchair usage. According to RESNA (Rehabilitation Engineering Society of North America), seat elevation for power wheelchairs (i.e. increasing seat height) is often medically necessary [8], and provides several benefits: improving the ability to perform activities of daily living (ADLs); facilitating transfers; providing psychological benefits by equalizing eye to eye contact with others (especially in

J.F. Borisoff is the Canada Research Chair in Rehabilitation Engineering Design at the British Columbia Institute of Technology (BCIT).

978-1-4673-6024-1/13/$31.00 ©2013 IEEE

Fig. 1. A user in the COMBO device using the dynamic seating functions.

Fig. 2. The COMBO device being used as a walking exoskeleton, with the wheeled frame deployed as a walker for stability. Note: straps (needed for secure attachment to the exoskeleton when standing) are not shown.

pediatric applications); enhancing independence and productivity; and positively impacting pain and secondary complications associated with wheelchair use [8]. Additionally, power wheelchairs can offer dynamic seat tilt, backrest recline, and standing [1, 6], which also enables activity and participation and provides health benefits [6-8]. The iBOT power wheelchair was shown to improve independent mobility [9] and is thought to enhance social participation through its capability for eye level communication [10], although this is achieved by raising a fixed seat rather than changing seated posture. Dynamic seating is also available in specialized manual tilt/recline wheelchairs, as well the "Elevation" ultra-light rigid wheelchair [11]. Dynamic wheeled mobility is an example of a trend in research programs that merge traditional AT, which fosters daily activities, with rehabilitation technology that provides built-in therapeutic benefits [3, 4].

Regardless of the acceptance of modern wheelchairs, obvious drawbacks remain, specifically regarding access, health, and general QoL. Standing and walking functions offer the potential to address these limitations, leading to the second evolving concept of ***powered walking exoskeletons***. These are complex powered orthotic devices capable of moving knee and hip joints through the patterns and range of motion necessary for walking. Several exoskeletons have been developed to restore standing and walking in people with disabilities [12-20]. These are slowly making commercial inroads – at this time through use in clinical rehabilitation settings [12-15], in the future through home versions.

RESNA documents the numerous benefits of standing as medically beneficial for wheelchair users by: enabling them to reach and improve ADLs; enhancing independence; improving bone density, circulation, and range of motion; reducing tone, spasticity, and the occurrence of pressure sores and skeletal deformities; and enhancing psychosocial well-being [5]. The importance of walking function through conventional therapy or AT (e.g. Lokomat robotic gait training) is becoming more apparent and widespread [21, 22], even in complete spinal cord injury (SCI) [21]. The benefits of standing and walking more often throughout the day has also been reiterated in the able-bodied population, with clear benefits to health (e.g. reducing diabetes) and even potential for increasing lifespan [23, 24].

Very recent studies have shown the potential of exoskeletons for providing significant therapeutic benefits, for

Fig. 3. The COMBO mobility device is shown with a user in a variety of positions from sitting to standing to walking.

example for secondary health complications that follow SCI, such as difficulties with bowel and bladder function, spasticity, cardiovascular function, body composition (e.g. bone density and fat), as well as QoL [12, 14, 15]. It is becoming increasingly clear that standing, walking, and exoskeletons are a central part of the future of mobility [16, 19].

While there is much excitement around exoskeletons, there are also serious usability and other concerns that hamper their current usefulness [16, 19]. Exoskeletons suffer from cumbersome slow gait and short travel range (which may leave a user stranded). These issues greatly limit their use as a general purpose daily mobility device [19], and could lead to device abandonment - a common problem with AT [3, 25]. As well, there are significant usability issues that need to be addressed. For example, donning or transferring into and out of the devices is awkward. Another issue is the lack of seating support for preventing skin issues associated with long-term use (e.g. where does the user sit when they arrive at a destination, and how are the buttocks protected in case of a fall?).

With these limitations, it is hard to envision exoskeletons replacing wheelchairs for normal daily activities in the near future. However, the use of wheels in unique combination with exoskeletons may offer a possible solution: a mobility device that can optimize daily activities and also provide long-term therapeutic benefits. These ideas have led to our ongoing design and development of the **CO**mbined **M**obility **B**ase-**O**rthosis (**COMBO)**, in essence a wheelchair combined with a detachable powered exoskeleton (Figs. 1 – 3).

II. Design Goals and Requirements

Our research and development projects follow an ISO 9001/13485 Quality System Process, modified where necessary in consideration of specific technology needs for people with disabilities. As such, the process is consistent with the Human, the Activity (and environment), and the Assistive Technology or HAAT model [26] as applied to developing novel devices. Briefly, the design process entails identifying needs, creating design requirements, conceptual design phase, detailed design, fabrication, validation, and iteration as necessary. The first three phases have been completed and are detailed here.

The need for the new COMBO mobility concept was detailed above. Considering how to encompass all the benefits of merging wheelchairs and exoskeletons has led to several specific design requirements (see Table I). The requirements are such that the design meets the functional capabilities of a typical manual rigid wheelchair in terms of transferring to and from the chair; seat cushioning adequate for all day sitting and pressure relief; and design and ergonomics that allow for efficient and long-range propulsion capabilities to support participation in the community and eliminating the risk of becoming stranded. As well, and by taking advantage of the integrated powered exoskeleton functionality, a full range of infinitely adjustable seating positions, including back recline, elevated seating, and standing, are possible, to match seating positions to suit activities (e.g. wheeling, reaching shelves, or face-to-face interactions with others). Most excitingly, the powered exoskeleton would detach when desired for walking sojourns, perhaps using the wheeled frame as a "walker", or

TABLE I. DESIGN REQUIREMENTS

Seating support consistent with existing modern wheelchairs
Transfer access adequate for all day use (e.g. ease of donning/doffing)
Efficient, long-range propulsion characteristics similar to wheelchairs
Manual wheeling capabilities (eliminating risk of becoming stranded)
Full range of adjustable dynamic seating positions available in real-time during normal wheelchair use, including: recline, elevated seating, declined (dumped) seating, and standing
Detachable powered exoskeleton functions for walking sojourns
Ability to use the wheeled frame as a walker, or with detachable crutches

with deployable crutches. This would foster greater access in a world designed for upright ambulation, and facilitate daily rehabilitation training since a user would always be sitting in his or her "rehabilitation device". We can imagine this leading to reduced abandonment and greater adherence to rehabilitative training as it would allow use of the device without need of taking the exoskeleton out the closet before donning the device (which could take a considerable amount of time and effort).

III. DESIGN CONCEPT AND RESULTS

We have used a 3D model of an end-user with anthropometry representative of a person with SCI to create an initial design concept for COMBO. The concept is a powered walking exoskeleton "docked" at the shanks to a wheeled frame. When attached together, the combination is analogous to a wheelchair with dynamic seating functions. This design concept has been modeled in Solidworks (Dassault Systems, Waltham, MA), and its basic functionality (i.e. frame and user movement from standing to sitting when exoskeleton attached) has been simulated and confirmed within the 3D design environment.

The walking exoskeleton component is similar to others under development (i.e. the ReWalk, Exso, and Vanderbilt exoskeletons [12, 15, 18]), along with additional componentry to facilitate docking to a wheeled frame and to support sitting. In the standing position, the exoskeleton shanks (i.e. lower legs) are mated to left and right front frame linkages of the wheeled frame via clamping mechanisms (Fig. 4, blue arrows). Once in this position, COMBO is analogous to a standing wheelchair, with a footplate firmly in contact with the floor to promote stability and safety. A user can then use the exoskeleton actuators in the knee and hip joints to lower into any seating position. Five key design elements facilitate the transformation of COMBO to and from an exoskeleton into a manual wheelchair with dynamic seating.

The first key to our design concept is a passive dynamic wheelchair positioning capability. As the exoskeleton lowers, the thigh sections eventually make contact with another part of the wheeled frame (Fig. 4, red arrows), causing the front frame linkages attached to the shanks to pivot and raise the feet off the ground (Fig 4, black arrows). At an appropriate seat angle, the feet are raised and COMBO can be maneuvered in a manner analogous to a manual wheelchair. This positioning process is completely passive in relationship to the wheeled frame, utilizing the built-in exoskeleton actuators and power.

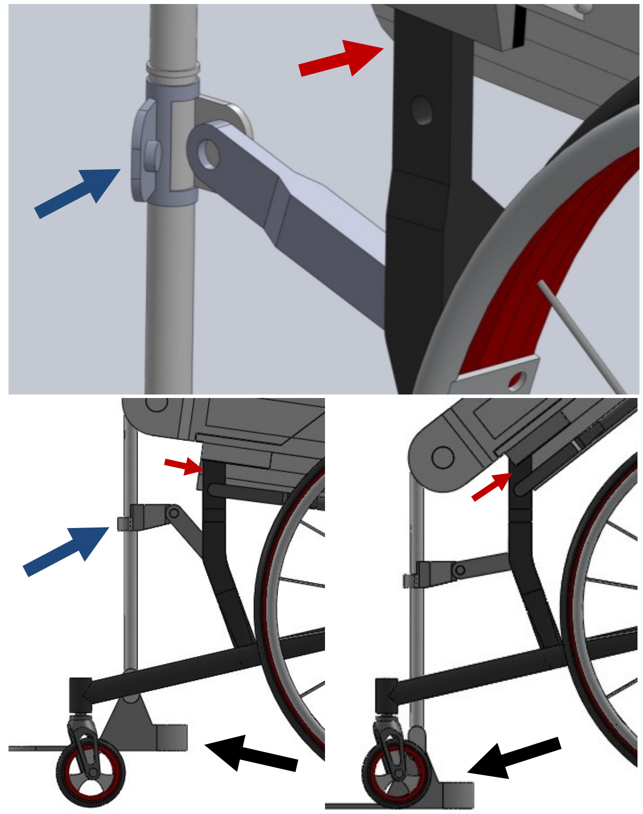

Fig. 4. Design details for exoskeleton attachment to wheeled frame.

The second key to our design concept aims to facilitate transfer access to and from the device. Wheelchair transfers are one of the highest-scored essential mobility skills for daily life [27]. This is a major limitation of exoskeletons due to the required alignment of device and user joints in order to minimize shear and galling (compare this to a wheelchair where the user sits on top of the frame instead of within it). One possible way the COMBO design could address this issue is through exoskeleton thigh sections capable of splitting into two sections, with internal motor and gears separated between the knee actuators and hip actuators. Here, the front thigh section, including knee joint and upper portion of the shank, would incorporate hinges and fold such that a small transfer base is formed adjacent to the seating area. Other detailed designs are under consideration and will be presented.

The third key to the design concept promotes frame rigidity. Due to the geometry of "hanging" the exoskeleton off the front of the wheeled frame (which may be too flexible), it is desired to include structure to support and stiffen COMBO when the exoskeleton is attached. This could be achieved using actuatable thigh-section clamps. A channel dorsal to each exoskeleton thigh section could be designed so that, as the exoskeleton lowers from the standing position, the upper bars of the wheelchair frame mate into each channel (Fig. 4, red arrows). When the exoskeleton stops moving, the channels clamp and grasp the upper bars of the frame. Our aim with this design is to create rigidity which will enable more of the push force translated into movement when COMBO is used as a manual wheelchair. It is also important that, when exoskeleton power is shut off, COMBO passively maintains rigidity and absolute seating position. This could be accomplished, for example, through joint actuators that fully brake in absence of power [18] and solenoid-actuated frame clamps.

The fourth key is passive deployable handles. As COMBO moves from sitting to standing, handles are passively raised via biased springs (which force the handles to an upright vertical position). When fully upright, the handles lock into position, transforming the wheeled frame into a walker (Figs. 2 and 3). Alternatively, the handles could be detachable crutches for less encumbered walking (Fig. 3).

The fifth key is integrated seating. The design of the exoskeleton thigh sections will incorporate a molded orthotic-like seat structure that wraps under the thigh and buttocks of the user. When the user is seated, each thigh section is aligned together such that a seat analogous to modern wheelchair cushions is formed. This design will support wheelchair transfers and long-term sitting (when attached to the frame, or when the user wants to sit on a bench or chair after walking somewhere). As well, the seat may be protective to the buttocks and hips in case of a fall while walking.

We are now moving into the detailed design phase of this research project, attempting to optimize design details while realizing the functional concepts described above. To support this phase of development, we have gathered external feedback on the design concept. In collaboration with the University of British Columbia, Occupational Therapy students conducted a series of focus groups with end users and industry professionals involved in the prescription and delivery of mobility devices. Results from the focus groups are currently being analyzed; however, a preliminary review of the findings indicates very positive support for the concept.

The findings also reinforced some known challenges and design limitations that had been identified throughout the design process. These concerns, which will be considered as the team moves forward with the design, include: the overall weight (and potentially the position of the centre of mass of the end user); the complexity of the mechanism for detaching and docking the exoskeleton, ensuring it be simple and quick; and creating a cushion that would be suitable for users with potentially complex seating needs, yet still allows full mobility when walking (this concern is being researched in collaboration with BCIT's Prosthetics and Orthotics Program). As much as possible, the team will continue to consult users throughout the development process to ensure relevancy and verify that the design meets end user needs.

Further regarding the issue of device size and weight, research efforts will be made to minimize these issues such that COMBO maintains adequate wheeling utility. Goldfarb and colleagues have made considerable strides in this area with their exoskeleton design that weighs ~27 lbs. currently, compared to others at >45 lbs. [18]. Our wheeled frame is estimated at this time to add about 15 lbs., including wheels, to the exoskeleton when attached; compare this combined weight to sports wheelchairs that often weigh over 40 lbs. [28]. Also, rigidity and centre of mass are also important to wheeling performance, areas that can be optimized in this concept. Finally, it would be possible to add a power wheeling option (e.g. with conventional add-on powered wheels), especially if control during wheeling is integrated with the exoskeleton controller and battery.

IV. Conclusion

The COMBO design concept merges the best features of walking exoskeletons with the benefits of wheeled mobility to create a novel mobility device with the potential of a significant benefit to the life of people with mobility impairments. COMBO could achieve more optimal mobility and seat positioning for all daily activities, and also support ongoing daily rehabilitation training both for functional improvements, as well as mitigating health deterioration over the long-term. The COMBO design would promote standing and walking as part of daily activities, as the user would normally be in the device during regular usage. And the integration of wheeled mobility promotes participation in community activities by ensuring a reliable and quick mobility option. Improving mobility through innovative engineering design can improve QoL, as well as help ameliorate social and financial costs.

Acknowledgment

We thank Jason Yu of BCIT's 3D Simulation Lab, Dan Leland and Dave Gans of BCIT, Bill Miller and Paula Rushton of the University of British Columbia, and Jocelyn Tomkinson of ICORD (International Collaboration On Repair Discoveries).

References

[1] R. A. Cooper, M. L. Boninger, D. M. Spaeth, D. Ding, S. Guo, A. M. Koontz, S. G. Fitzgerald, R. Cooper, A. Kelleher and D. M. Collins, "Engineering better wheelchairs to enhance community participation," *IEEE Trans. Neural Syst. Rehabil. Eng.,* vol. 14, pp. 438-455, Dec, 2006.

[2] J. Wee and R. Lysaght, "Factors affecting measures of activities and participation in persons with mobility impairment," *Disabil. Rehabil.,* vol. 31, pp. 1633-1642, 01/01; 2012/08, 2009.

[3] R. E. Cowan, B. J. Fregly, M. L. Boninger, L. Chan, M. M. Rodgers and D. J. Reinkensmeyer, "Recent trends in assistive technology for mobility," *J. Neuroeng Rehabil.,* vol. 9, pp. 20, Apr 20, 2012.

[4] D. J. Reinkensmeyer, P. Bonato, M. L. Boninger, L. Chan, R. E. Cowan, B. J. Fregly and M. M. Rodgers, "Major trends in mobility technology research and development: overview of the results of the NSF-WTEC European study," *J. Neuroeng Rehabil.,* vol. 9, pp. 22, Apr 20, 2012.

[5] J. Arva, G. Paleg, M. Lange, J. Lieberman, M. Schmeler, B. Dicianno, M. Babinec and L. Rosen, "RESNA position on the application of wheelchair standing devices," *Assist. Technol.,* vol. 21, pp. 161-8; quiz 169-71, Fall, 2009.

[6] D. Ding, E. Leister, R. A. Cooper, R. Cooper, A. Kelleher, S. G. Fitzgerald and M. L. Bonniger, "Usage of tilt-in-space, recline, and elevation seating functions in natural environment of wheelchair users." *Journal of Rehabilitation Research and Development,* vol. 45, pp. 973-984, 2008.

[7] B. E. Dicianno, J. Arva, J. M. Lieberman, M. R. Schmeler, A. Souza, K. Philips, M. Lange, R. Cooper, K. Davis and K. L. Betz, "RESNA position on the application of tilt, recline, and elevating legrests for wheelchairs." *Assistive Technology,* vol. 21, pp. 13-22, 2009.

[8] J. Arva, M. R. Schmeler, M. L. Lange, D. D. Lipka and L. E. Rosen, "RESNA position on the application of seat-elevating devices for wheelchair users," *Assist. Technol.,* vol. 21, pp. 69-72; quiz 74-5, Summer, 2009.

[9] H. Uustal and J. L. Minkel, "Study of the Independence IBOT 3000 Mobility System: an innovative power mobility device, during use in community environments," *Arch. Phys. Med. Rehabil.,* vol. 85, pp. 2002-2010, Dec, 2004.

[10] S. Arthanat, J. M. Desmarais and P. Eikelberg, "Consumer perspectives on the usability and value of the iBOT((R)) wheelchair: findings from a case series," *Disabil. Rehabil. Assist. Technol.,* vol. 7, pp. 153-167, Mar, 2012.

[11] J. F. Borisoff and L. T. McPhail, "The development of an ultralight wheelchair with dynamic seating." in *Proceedings of the 2011 Annual RESNA Conference,* Toronto, ON, 2011, pp. 1-4.

[12] A. M. Spungen. Walking with an exoskeleton for persons with paraplegia. *Interdependence 2012 Abstract Book* pp. 19. 2012.

[13] G. Zeilig, H. Weingarden, M. Zwecker, I. Dudkiewicz, A. Bloch and A. Esquenazi, "Safety and tolerance of the ReWalk™ exoskeleton suit for ambulation by people with complete spinal cord injury: a pilot study." *The Journal of Spinal Cord Medicine,* vol. 35, pp. 96-101, 2012.

[14] A. Esquenazi, M. Talaty, A. Packel and M. Saulino, "The ReWalk Powered Exoskeleton to Restore Ambulatory Function to Individuals with Thoracic-Level Motor-Complete Spinal Cord Injury," *Am. J. Phys. Med. Rehabil.,* vol. 91, pp. 911-921, Nov, 2012.

[15] S. Kirshblum. Technological advances in SCI. *Interdependence 2012 Abstract Book* pp. 18. 2012.

[16] H. Herr, "Exoskeletons and orthoses: Classification, design challenges and future directions," *Journal Or NeuroEngineering and Rehabilitation,* vol. 6, pp. 21, 2009.

[17] K. Suzuki, G. Mito, H. Kawamoto, Y. Hasegawa and Y. Sankai, "Intention-based walking support for paraplegia patients with robot suit HAL," *Advanced Robot,* vol. 21, pp. 1441-1469, 2007.

[18] R. J. Farris, H. A. Quintero and M. Goldfarb, "Preliminary Evaluation of a Powered Lower Limb Orthosis to Aid Walking in Paraplegic Individuals," *Neural Systems and Rehabilitation Engineering, IEEE Transactions On,* vol. 19, pp. 652-659, 2011.

[19] J. L. Pons, "Rehabilitation exoskeletal robotics. The promise of an emerging field." *IEEE Engineering in Medicine and Biology Magazine,* vol. 29, pp. 57-63, 2010.

[20] P. D. Neuhaus, J. H. Noorden, T. J. Craig, T. Torres, J. Kirschbaum and J. E. Pratt, "Design and evaluation of Mina: a robotic orthosis for paraplegics," *IEEE Int. Conf. Rehabil. Robot.,* vol. 2011, pp. 5975468, 2011.

[21] R. R. Roy, S. J. Harkema and V. R. Edgerton, "Basic Concepts of Activity-Based Interventions for Improved Recovery of Motor Function After Spinal Cord Injury," *Arch. Phys. Med. Rehabil.,* vol. 93, pp. 1487-1497, 9, 2012.

[22] A. Domingo, T. Lam, D. L. Wolfe and J. J. Eng, Eds., *Lower Limb Rehabilitation Following Spinal Cord Injury.* Vancouver: 2012.

[23] P. T. Katzmarzyk and I. Lee, "Sedentary behaviour and life expectancy in the USA: a cause-deleted life table analysis," *BMJ Open,* vol. 2, January 01, 2012.

[24] E. G. Wilmot, C. L. Edwardson, F. A. Achana, M. J. Davies, T. Gorely, L. J. Gray, K. Khunti, T. Yates and S. J. Biddle, "Sedentary time in adults and the association with diabetes, cardiovascular disease and death: systematic review and meta-analysis," *Diabetologia,* vol. 55, pp. 2895-2905, Nov, 2012.

[25] E. Biddiss and T. Chau, "Upper-limb prosthetics: critical factors in device abandonment." *American Journal of Physical Medicine & Rehabilitation,* vol. 86, pp. 977-987, 2007.

[26] A. M. Cook and J. M. Polgar, *Cook and Hussey's Assistive Technologies: Principles and Practice.* Mosby, 2007.

[27] O. Fliess-Douer, Y. C. Vanlandewijck and L. H. V. Van Der Woude, "Most Essential Wheeled Mobility Skills for Daily Life: An International Survey Among Paralympic Wheelchair Athletes With Spinal Cord Injury," *Arch. Phys. Med. Rehabil.,* vol. 93, pp. 629-635, 4, 2012.

[28] B. S. Mason, L. H. van der Woude and V. L. Goosey-Tolfrey, "Influence of glove type on mobility performance for wheelchair rugby players," *Am. J. Phys. Med. Rehabil.,* vol. 88, pp. 559-570, Jul, 2009.