2019 IEEE International Conference on Advanced Robotics and its Social Impacts (ARSO)
BIT, Beijing, China. October 31 - November 2, 2019

Pilot Study on the Needs of Prospective Exoskeleton Users with Impaired Mobility

Namita Anil Kumar[1], Shawanee' Patrick[1], and Pilwon Hur[2]

Abstract— **Patients with paraplegia and spinal cord injuries stand to benefit greatly from powered exoskeletons physically, socially, and psychologically. Yet, most powered exoskeletons are limited to usage in rehabilitation clinics or academic facilities. To overcome the challenge of commercialization it is necessary to better understand the needs of potential exoskeleton users. A customer needs survey was conducted among 14 participants with mobility disorders. The data collected was analyzed using a House of Quality. The results emphasized a need to direct research towards designing exoskeletons that can balance without crutches and impose minimal interaction forces upon the user. While doing so, researchers should also pay keen attention to the cost of the exoskeleton.**

I. INTRODUCTION

A 2016 study showed that 28% of the US population suffer from walking disabilities [1]. A major cause of such disabilities is Spinal Cord Injuries (SCI) with an annual estimate of 17,700 newly reported cases. Of the cases reported since 2015, 20.2% suffer from complete paraplegia while 20.4% suffer from incomplete paraplegia [2]. Also, about 90% of those with complete SCI rely on wheelchairs for mobility [3]. Extended usage of wheelchairs has many side effects such as osteoporosis, spasticity, urinary tract infections, increased body mass index, impaired digestive, lymphatic, and vascular functions, pressure sores, and depression [4]–[8]. For individuals that are restricted to wheelchairs, the ability to stand at eye level with others carries high psychosocial significance [7], [9]. There are also studies that show walking over long periods of time can improve the quality of life and result in psychological benefits. Utilizing powered exoskeletons could solve several problems SCI patients face. There are currently many research groups focusing on the development of powered lower-limb exoskeletons [10]–[14]. These groups employ an actuated hip and knee design. The powered exoskeletons Ekso GT by Ekso Bionics and ReWalk Personal by ReWalk utilize a spring loaded ankle joint [10], [11]. A notable aspect of the Ekso GT is that the assistance provided by the robotic system to the user can be varied. Thus, it may be used by patients with minor mobility disorders (like foot drop) to severe disabilities like paraplegia. The ReWalk is one of the few commercially available exoskeletons that can be used as a personal device on a daily basis. Mina V2 by IHMC is one of the few exoskeletons with a powered ankle joint [14]. While all of the previously mentioned exoskeletons depend on hand-held crutches for balance, the Rex exoskeleton from REX Bionics is a self balancing exoskeleton [13]. It implements Zero-Moment-Point (ZMP) based controllers to ensure stability. But, to achieve said stability, the speed of the generated gait was greatly reduced. Additionally, it is the only exoskeleton that employs 5 actuators per limb [13].

Despite the advances made by such groups, the application of most powered lower-limb exoskeletons is limited to rehabilitation clinics and academic facilities. To understand the cause of said limitation, clinical studies were conducted to investigate the efficacy, safety, and ergonomics of the designs. A European study conducted at rehabilitation centers revealed that extensive usage of exoskeletons led to ankle swelling and pressure sores [15]. It is believed that the straps used to affix the exoskeleton to the user shear against the user's limbs and ultimately lead to pressure sores [16], [17]. Another commonly reported complaint is the extensive amount of time required to don the exoskeleton [16]. Additionally, several sessions are necessary to fine-tune the adjustments and ensure a fit to the subject [16]. The lack of actuation at the ankle in most exoskeletons is a concerning fact since the ankle is responsible for bearing the user's weight and providing the propulsion required for healthy walking. Another possible improvement is the elimination of crutches for balance without having to reduce the walking speed.

The prior passages presented an account from a developer's perspective. However, for successful commercialization of exoskeletons, it is critical to present an account from a customer's perspective by gathering information on customer needs. By designing in accordance to the user's needs, one is assured of user satisfaction and fewer design iterations; thereby strengthening the socio-economic impact of the product [18]. Unfortunately, to the authors' knowledge, there is no published data on the needs of SCI patients. This paper aims to address this gap in knowledge and lay the foundation for establishing target specifications or quantified standards for exoskeleton design. The primary method utilized a customer-needs survey wherein participants rated the importance of subjective needs such as comfort and durability (Section II). These needs were then translated into design metrics using a House of Quality (HOQ)–the first step of Quality Function Deployment (QFD) [18]. In addition to studying the relationship between the needs and the metrics, the HOQ also

*This work was not supported by any organization

[1]Namita Anil Kumar and Shawanee' Patrick contributed equally to this paper. They are graduate students at the Department of Mechanical Engineering, Texas A&M University, College Station, TX 77843, USA. namita.anilkumar@tamu.edu, shawaneepatrick@tamu.edu

[2]Pilwon Hur is with faculty of the Department of Mechanical Engineering Engineering, Texas A&M University, College Station, TX 77843, USA pilwonhur@tamu.edu

studies how the metrics correlate. The results of the HOQ include the absolute and relative weights of the metrics. The HOQ has been detailed in Section III while its results have been discussed in Section IV.

II. CUSTOMER SURVEY

A. Participant Population

The desired population for this study were spinal cord injury (SCI) patients and those with extremely limited lower limb mobility. Participants must be dependent on mobility aids to walk on a regular basis. So far 14 responses from the desired population have been recorded. The disorders of the participants included muscular dystrophy and SCI. All subjects currently use wheelchairs for mobility. When asked whether they would be interested in using an exoskeleton, all but one responded positively. Nonetheless, all participants quoted a strong desire for independence and mobility with an exoskeleton.

B. Survey Design

The survey was conducted online utilizing Qualtrics. Participants for this study were recruited using Texas A&M Bulk email, and social media posts. This survey was approved by Texas A&M University's Institutional Review Board (IRB) (IRB2017-0788). Participants gave their consent on the first page of the survey. The survey included screening questions to exclude able-bodied participants and those who do not use mobility aids. The goal of the survey was to assess the needs that are most important to potential users. The questions asked in the survey fell under the following categories:

- Demographics
- Screening Questions
- Injury type/ Muscle usage
- Use of mobility aids
- Reasons for discontinuing use of mobility aids
- Importance of design needs of exoskeletons
- Amount willing to invest
- General interest in using an exoskeleton

The goal for asking about previous mobility aids was to determine possible factors to consider when developing an exoskeleton device. The participants were asked about their history of usage and/or reason for ceasing use of wheelchairs, Hip-Knee-Ankle-Foot-Orthoses (HKAFO), and powered exoskeletons. The design needs for the exoskeleton were determined after speaking with Dr. Kelly Lobb, a physician at a local rehabilitation hospital, and by surveying literature. The survey also allowed users to include custom design needs and rank them as well. Table I lists the needs and their description.

The subjects were asked to rate the needs as: *Very Important*, *Rather Important*, *Important*, *Not that important*, *Not required*. The ratings were converted to a numerical scale of 5 to 1, with 5 corresponding to *Very Important*. The average score of each need has been recorded in the third column of Table I. Subjects were also asked to rank the needs in the order of importance. The fourth column of Table I reports the average ranking. Note that values closer to one reflect a higher ranking. The need pertaining to the exoskeleton's cost was represented by six price brackets: *Less than* \$20,000, \$20,000-\$40,000, \$40,000-\$60,000, \$80,000-\$100,000, \$100,000-\$150,000, and \$150,000 *or more*. The recorded selections were converted to 1-5 linear scale, with 5 corresponding to *Less than* \$20,000.

III. PROCESSING SURVEY RESULTS

To combine the scores from the rating and ranking, the latter was converted to a scale similar to that of ratings (i.e. scale of 1 to 5) and then summed with the rating scores. The final value has been reported in the final column of Table I. The rating score regarding cost was doubled. A HOQ was used to convert the needs and their importance values to quantified metrics. The template was acquired from QFD online [19]. A total of 25 metrics were established based on exoskeleton design parameters reported in literature. Further, the relationship between the metrics and the needs were categorized as *strong*, *moderate*, or *weak*. Among the 25 resulting metrics a few notable ones have been presented below. Also noted is the relationship between the listed metrics and some of the needs.

Volume of the deployed exoskeleton: The volume occupied by the exoskeleton and a user of average height and weight, while standing. This metric shares a strong relationship with the needs regarding compactness, appearance, and whether the system is hands-free, while it is weakly related to the need for easy assembly and operation.

Range of operable stride lengths: The range of stride lengths that can be accommodated while walking. This metric is strongly related to the user's comfort and desired walking speed. The accommodation of different stride lengths also results in human-like walking.

Steps to get in and out of the system: The number of steps required to wear and remove the exoskeleton should be reduced to make the exoskeleton easier to don.

Battery life in hours: The amount of time the device's battery lasts on a single charge while standing. This metric is also dependent on whether the device is hands-free.

Peak motor torque: The maximum motor torque required while a user (of average height and weight) walks with the exoskeleton. Naturally, this metric depends on the walking speed and whether the device is hands-free.

Maximum factor of safety of structural elements: The factor of safety used to design structural elements of the exoskeleton. A higher factor of safety generally implies a more durable product.

Maximum difference from human trajectories: The amount by which the generated joint trajectories of the user with the exoskeleton deviate from natural human walking trajectories.

Maximum interaction forces between the user and the exoskeleton: The maximum force recorded while walking at the exoskeleton's straps. As reported by studies [16], [17], considerable interaction forces at the straps lead to pressure sores. This metric is thus related to user comfort.

Ability to balance without crutches: A binary evaluation

TABLE I

LIST OF NEEDS, THEIR DESCRIPTION AND SCORES. A HIGHER RATING AND LOWER RANK SIGNIFIES MORE IMPORTANCE.

Need	Description	Rated score	Ranking score	Final score (F_i)
Comfort	Does not cause pain or uneasiness	4.4	3.4	8.6
Appearance	Visually appealing or sleek	2.4	10.0	4.4
Hands free	No need for crutches/walker	3.8	4.1	7.7
Easy to put on	Can be donned with little to no additional assistance	3.8	5.2	7.4
Easy to assemble	Minimal work to assemble	3.6	6.7	6.7
Easy to operate	Straight forward operation strategy	3.5	6.4	6.7
Natural walking	Walking mimics able-bodied walking	3.5	8.2	6.1
Light weight	Easy to move the exoskeleton to another location	3.9	7.1	6.9
Compact	Amount of space when wearing	3.1	10.2	5.1
Speed	Ability to select a preferred walking speed	2.6	10.4	4.5
Battery life	The amount of time a single battery charge can last	3.7	6.9	6.8
Durability	Longevity of the device	4.1	8.7	6.5
Storage space	Availability of a storage compartment in the exoskeleton	2.8	12.9	3.8
Low Maintenance	Minimal maintenance to ensure the device is operational	3.5	10.5	5.3
Economical	Preferred price brackets	3.3	–	6.6

of whether crutches are required for balancing while using the exoskeleton for walking. In addition to deciding whether the exoskeleton is hands-free, this metric is also related to needs such as appearance and compactness of the device.

Cost: The amount required to manufacture one unit of the product (exoskeleton). This metric is strongly impacted by all needs except the ease of donning, assembly, and operation.

A comprehensive list of the 25 metrics has been provided in the appendix. Fig. 1 depicts the relationship between the prior listed metrics and the needs. The row immediately above the metrics reflects the desired direction of improvement in metrics; i.e. whether a metric should be increased or decreased. Note that the metric regarding the *ability to balance without crutches* is a binary target. The roof of the HOQ also consists of the correlation between metrics. For instance, increasing the *range of stride lengths* accommodated by the device will likely lower the *battery life* and increase *peak motor torque*. On the contrary, customizing the *stride length* to the user's comfort will likely lower *interaction forces* between the exoskeleton and user. The correlations between metrics are categorized as *strong positive*, *positive, negative*, *strong negative*. The metrics that have no correlations are left blank. These correlations help to understand the design challenge associated with optimizing each metric. A metric with more negative correlations is one that is considered harder to optimize. Note that a metric with more positive correlations does not imply ease of optimization. It must be stressed that the HOQ in Fig. 1 only analyzes the previously discussed metrics. The results from the HOQ have been presented in Table II.

The absolute weight of a metric, k, is determined by a weighted sum (W_k) of the relationships between the metric under consideration and the needs (refer Fig. 1). Let R_{ik} represent the relationship between need i and metric k. A *strong* relationship is assigned a score of 9, while *moderate* and *weak* relationships are assigned scores 3 and 1, respectively. The weight (F_i) of the sum is equal to the final score of need i from Table I.

$$W_k = \sum_{i=1}^{15} R_{ik} F_i \tag{1}$$

Among the metrics discussed the most important metric was the ability to balance without crutches.

IV. DISCUSSION

The survey data revealed that potential users want an exoskeleton that is (i) comfortable, (ii) hands-free, and (iii) easy to don. The three most important metrics of the HOQ are the *ability to balance without crutches*, *cost*, and *interaction forces between the user and the exoskeleton*. This section discusses the relationship between the highly weighted needs and metrics. Though the participants did not rate the need related to cost highly, the associated metric received a high relative weight. This is due to the strong relationships shared by the *cost* metric with other needs. Since comfort received the highest score, it is reasonable that the metric regarding *interaction forces* was weighted highly in the HOQ. A possible method of reducing interaction forces is by redesigning the straps of the exoskeletons. Another major design challenge, while assuring the user's comfort, is accommodating the knee's complex motion. Unlike the conventional knee mechanisms found in exoskeletons, the human knee is not a pin-joint [20]. Thus, the rotational axis of the exoskeleton and the user's knee tend to misalign. To compensate for the misalignment, the exoskeleton's straps tend to shift around, thereby increasing the interaction forces that eventually cause pressure sores. The misalignment in rotational axes also increases the time required to don the exoskeleton since wearers are required to spend an extended

TABLE II

LIST OF THE METRICS AND THEIR RELATIVE WEIGHTS.

Metric	Relative weight
Volume of deployed mechanism	4.7
Range of operable stride length	4.7
Steps to get in and out of the system	3.3
Battery life in hours	4.7
Peak motor torque	4.6
Maximum factor of safety of structural elements	4.9
Maximum difference from human trajectories	3.4
Maximum interaction forces	5.2
Ability to balance without crutches	8.4
Cost	6.6

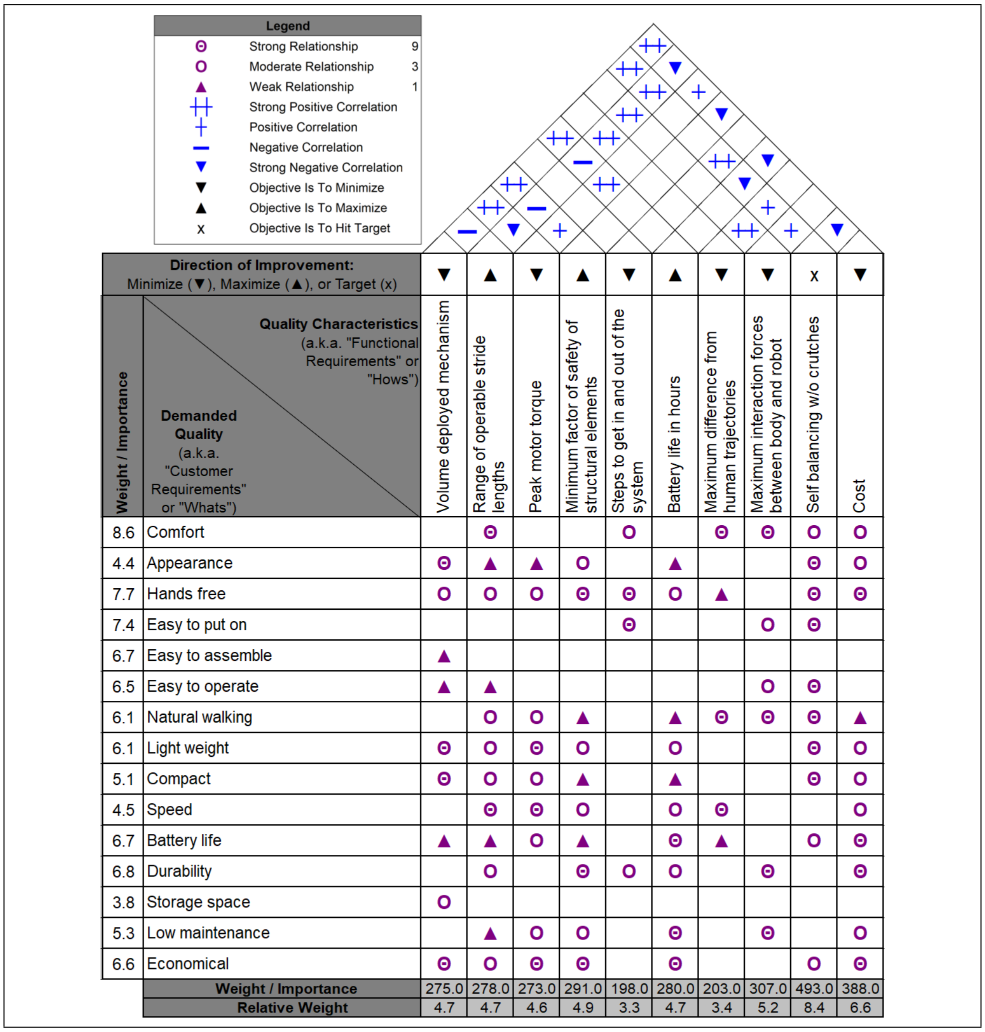

Fig. 1. House of quality depicting the metrics discussed. Powered by QFD Online [19]

period of time reducing the misalignment [21]. Despite the highly scored need for easy donning, the metric *steps to get in and out of the device* was deemed to be of low importance by the HOQ. This is because the metric is not related to the other needs. A possible approach to combating misalignment of the axes is to implement a self-aligning mechanism. Some researchers have attempted this [21], [22], but there is room for improvement in simplifying the mechanisms.

The metric, *range of operable stride lengths*, was found to have the most negative correlations with other metrics; making it the hardest to optimize. This metric is directly related to the allowable range of walking speed. Exoskeleton developers are struggling to overcome this challenge due to limitations in current motor technology. Motors with the required torque will result in increased weight and cost, making the device infeasible to use. Further, the dependence of the state of the art exoskeletons on crutches (for balance) severely limits the walking speed. This fact is apparent in the roof of the HOQ, which indicates a strong positive correlation between the metrics *range of operable stride lengths* and *self balancing without crutches*. By exploiting this positive relationship, one could possibly optimize the *range of operable stride lengths* without severely affecting the other metrics. In other words, eliminating the need for crutches could help alleviate some concerns surrounding the optimization of *range of operable stride lengths*.

Balancing without crutches is important since most powered exoskeletons on the market utilize crutches for balance. The associated metric is strongly related to most of the other needs, thus making it the highest weighted metric. It's high relative weight emphasizes the need for designing self-balancing exoskeletons. The REX exoskeleton assures self-balancing at the expense of walking speed [13]. Another group that has attempted to solve the issue of balancing exoskeletons is the Delft Biorobotics Lab. Their solution utilizes a gyroscope to assist in balancing [23]. It is hoped that their tests with human subjects will be successful and the results can be incorporated with exoskeletons. Prior to designing balance mechanisms one must describe balance in terms of quantified metrics. This study limited itself to a binary metric of whether or not the crutches are required to balance. Further studies are required to better define walking balance. Some potential metrics include angular momentum of the user and exoskeleton, and the extent of push recovery.

Other metrics that could be better defined include the *steps to get in and out of the exoskeleton*. This metric may change based on whether the user is seated or standing prior to wearing the device. The survey could also be improved by asking the user their preferred way of donning the device (i.e. from a seated or standing position). Another potential question is whether users would appreciate steering assistance since current exoskeletons require users to manually orient themselves using their crutches. Further, any user of an exoskeleton device must undergo training sessions to get acclimated. Such training sessions necessitate the presence and involvement of therapists. Thus, there is a strong need to study and understand the needs of therapists.

In addition to refining the survey and better defining metrics, there is a need to establish target values for the metrics. For instance, the maximum amount of interaction forces that is admissible should be investigated. Such target specifications can be established through clinical studies and analysis using biomechanical models.

V. CONCLUSION AND FUTURE WORK

A survey conducted among 14 participants with reduced mobility revealed a strong need for hands-free exoskeletons that assure comfort and mobility. The needs of the participants were translated into engineering metrics using a HOQ. The HOQ analysis revealed that the most important design metrics are self-balancing, cost, and minimal interaction forces between the user and the exoskeleton. Designers must consider these factors to help design powered exoskeletons that fully meet user needs. Doing so will also increase the social and psychological benefits of the device.

In order further solidify these findings more participants are required. The survey will be improved upon to ensure that all questions and choices are clear and easy to understand. In order to properly use an exoskeleton, patients must be trained. Therapists are typically needed for this process. Therefore, in the future the survey will be extended to therapists in order to fully assess the needs that exoskeletons must satisfy.

Biomechcanical studies will be conducted to better define balance using an exoskeleton. Consecutively, target values for the resulting metrics will be determined. In regards to the interaction forces between the user and exoskeleton, studies will be conducted to pin-point what aspects of the exoskeleton lead to high interaction forces. Additionally, attempts will be made to measure the amount of interaction forces that is acceptable before causing discomfort to the users.

APPENDIX

Table III lists the 25 metrics considered in the HOQ and their relative weights. In addition to the interaction forces between the user and exoskeleton, the list includes a metric regarding the interaction forces at the user's joints. Note that the metric regarding gait symmetry encompasses both kinematic and kinetic symmetry.

TABLE III
LIST OF ALL METRICS AND THEIR RELATIVE WEIGHT.

Metric	Relative weight
Range of automated steering	2.3
Heat generated	3.4
Power consumed	3.3
Volume deployed mechanism	4.7
Range of operable speeds	2.1
Steps to assemble	2.9
Steps to operate	3.1
Life cycles	3.8
Human energy consumption in one gait cycle	3.1
Range of body support that can be provided	4.6
Range of operable stride lengths	4.7
Range of acceptable user weight	3.9
Range of acceptable user height	3.9
Peak motor torque	4.6
Minimum factor of safety of structural elements	4.9
Volume of packaging box	3.2
Steps to get in and out of the system	3.3
Battery life in hours	4.7
Interaction forces at lower-limb joints	2.6
Maximum difference from human trajectories	3.4
Maximum interaction forces	5.2
Self balancing w/o crutches	8.4
Symmetry in gait	3.2
Weight of final product	4.1
Cost	6.6

ACKNOWLEDGMENT

Authors thank Dr. Kelly Lobb who is a physician at St. Joseph Rehabilitation Hospital, College Station, TX.

REFERENCES

[1] L. Kraus, "2016 Disability Statistics Annual Report," University of New Hampshire, Durham, Tech. Rep., 2017. [Online]. Available: www.iod.unh.edu

[2] National Spinal Cord Injury Statistical Center, "Spinal Cord Injury Facts and Figures at a Glance," National Spinal Cord Injury Statistical Center, Birmingham, Tech. Rep., 2018. [Online]. Available: www.msktc.org/sci/model-system-centers.

[3] S. C. Kirshblum, S. P. Burns, F. Biering-Sorensen, W. Donovan, D. E. Graves, A. Jha, M. Johansen, L. Jones, A. Krassioukov, M. Mulcahey, M. Schmidt-Read, and W. Waring, "International standards for neurological classification of spinal cord injury (Revised 2011)," *The Journal of Spinal Cord Medicine*, vol. 34, no. 6, p. 535, 2011.

[4] L. Noreau, P. Proulx, L. Gagnon, M. Drolet, and M.-T. Laramée, "Secondary Impairments After Spinal Cord Injury," *American Journal of Physical Medicine & Rehabilitation*, vol. 79, no. 6, pp. 526–535, nov 2000.

[5] K. T. Ragnarsson, "Functional electrical stimulation after spinal cord injury: current use, therapeutic effects and future directions," *Spinal Cord*, vol. 46, no. 4, pp. 255–274, apr 2008.

[6] "Spinal Cord Injury-Induced Osteoporosis: Pathogenesis and Emerging Therapies," *Current Osteoporosis Reports*, vol. 10, no. 4, pp. 278–285, dec 2012.

[7] 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, no. 2, pp. 96–101, 2012.

[8] N. Gustafson, "Spinal Cord Injury - A Guide for Patient and Family," *American Journal of Occupational Therapy*, vol. 42, no. 10, pp. 682–682, oct 1988.

[9] A. L. Hicks, K. A. Martin, D. S. Ditor, A. E. Latimer, C. Craven, J. Bugaresti, and N. McCartney, "Long-term exercise training in persons with spinal cord injury: effects on strength, arm ergometry performance and psychological well-being," *Spinal Cord*, vol. 41, no. 1, pp. 34–43, jan 2003.

[10] K. A. Strausser and H. Kazerooni, “The development and testing of a human machine interface for a mobile medical exoskeleton,” in *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, sep 2011, pp. 4911–4916.

[11] M. Talaty, A. Esquenazi, and J. E. Briceno, “Differentiating ability in users of the ReWalk^{TM} powered exoskeleton: An analysis of walking kinematics,” in *2013 IEEE 13th International Conference on Rehabilitation Robotics (ICORR)*. IEEE, jun 2013, pp. 1–5.

[12] H. A. Quintero, R. J. Farris, and M. Goldfarb, “A Method for the Autonomous Control of Lower Limb Exoskeletons for Persons With Paraplegia,” *Journal of Medical Devices*, vol. 6, no. 4, p. 041003, oct 2012.

[13] R. Little and R. Alexander Irving, “Self contained powered exoskeleton walker for a disabled user,” sep 2015. [Online]. Available: https://patents.google.com/patent/US20160067137A1/en

[14] R. Griffin, T. Cobb, T. Craig, M. Daniel, N. van Dijk, J. Gines, K. Kramer, S. Shah, O. Siebinga, J. Smith, and P. Neuhaus, “Stepping Forward with Exoskeletons: Team IHMC’s Design and Approach in the 2016 Cybathlon,” *IEEE Robotics & Automation Magazine*, vol. 24, no. 4, pp. 66–74, dec 2017.

[15] N. Evans, C. Hartigan, C. Kandilakis, E. Pharo, and I. Clesson, “Acute Cardiorespiratory and Metabolic Responses During Exoskeleton-Assisted Walking Overground Among Persons with Chronic Spinal Cord Injury,” *Topics in Spinal Cord Injury Rehabilitation*, vol. 21, no. 2, pp. 122–132, mar 2015.

[16] A. S. Gorgey, “Robotic exoskeletons: The current pros and cons,” *World Journal of Orthopedics*, 2018.

[17] B. Chen, H. Ma, L.-Y. Qin, F. Gao, K.-M. Chan, S.-W. Law, L. Qin, and W.-H. Liao, “Recent developments and challenges of lower extremity exoskeletons,” *Journal of Orthopaedic Translation*, vol. 5, pp. 26–37, apr 2016.

[18] K. T. Ulrich and S. D. Eppinger, *Product design and development*. McGraw-Hill, 1995.

[19] Q. Online, “QFD Online.” [Online]. Available: http://www.qfdonline.com/

[20] M. Wilcox, A. Rathore, D. Z. Morgado Ramirez, R. C. Loureiro, and T. Carlson, “Muscular activity and physical interaction forces during lower limb exoskeleton use,” *Healthcare Technology Letters*, vol. 3, no. 4, pp. 273–279, 2016.

[21] V. A. D. Cai, P. Bidaud, V. Hayward, and F. Gosselin, “Self-adjustment mechanisms and their application for orthosis design,” *Meccanica*, vol. 52, no. 3, pp. 713–728, feb 2017.

[22] B. Celebi, M. Yalcin, and V. Patoglu, “AssistOn-Knee: A self-aligning knee exoskeleton,” in *2013 IEEE/RSJ International Conference on Intelligent Robots and Systems*. IEEE, nov 2013, pp. 996–1002. [Online]. Available: http://ieeexplore.ieee.org/document/6696472/

[23] D. Lemus, J. van Frankenhuyzen, and H. Vallery, “Design and Evaluation of a Balance Assistance Control Moment Gyroscope,” *Journal of Mechanisms and Robotics*, vol. 9, no. 5, p. 051007, aug 2017.