Assessment of User Needs in the Design of a Wearable Robot for Neuroehabilitation

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Abstract: Robot-assisted rehabilitation systems have been clinically proven to be just as effective in stroke rehabilitation as with the traditional methods. In particular, robotic exoskeletons for the upper limbs are powered wearable devices designed to be aligned with the user's joints and linkages. Current methods in product design simplifies the complex requirements of the human upper limb, thereby compromising the comfort and safety of the injured patient. In rehabilitation robotics, it is important to consider the user needs and requirements of such a device early in its design phase. This study demonstrates how the assessment of user needs participate in the design of a wearable robot for the rehabilitation of Filipino and Asian patients. A review of existing devices and their design features was presented to rehabilitation doctors from the Philippine General Hospital which was followed by an interview about their own experiences during therapy. The results of the discussion were translated into a list of user requirements for wearable robots in neurorehabilitation. After which, corresponding importance ratings from both the design engineers and their medical collaborators were assigned to arrive with a matrix that determines the final design priorities and specifications of the device. This study was successful in evaluating at least fifteen (15) of the user needs in consideration. The results of this study was then used in the design of a 7-degree-of-freedom robotic exoskeleton for patiens with Filipino and Asian body types. This approach enables medical device developers to have prior knowledge of existing design problems and use it to incorporate user-centricity and compatibility with their current design.

Key Words: User Needs Analysis; Product Design; Rehabilitation Robotics; Stroke Rehabilitation; Robotic Exoskeletons

1. INTRODUCTION

Motor rehabilitation involving the Central Nervous System (CNS) still remains as one of the most challenging hurdles the medical research community is facing. CNS disorders are caused by various incidents such as stroke, traumatic-brain injuries (TBI), and spinal cord injuries (SCI). About 10.3 million new strokes occurred in 2013, 67% of which were ischemic which means that there was a restriction of blood supply in the brain leading to the incident (Benjamin et al., 2017). A person who has experienced and survived stroke is expected to continue the rest of his/her life in disability if not treated properly (Mukherjee and Patil, 2011). In the developing regions, therapy options for stroke are less accessible. Such in the case of the Philippines where a 0.9% stroke prevalence was determined based on recent data (Navarro et al., 2014). Furthermore, CNS injuries caused by accidents in work, sports, and aging also remain in the country's priority list for health research and development (WHO, 2011; DOH, 2010).

Intervention via repetitive and task-oriented training during physical therapy makes it possible to regain motor function due to neuroplasticity (Schaechter, 2004). Robot-assisted rehabilitation systems have been able to provide an obvious improvement, or in some cases, more efficient in regaining motor function after stroke (Chang and Kim, 2013). In particular, end-effector robots and wearable robotic exoskeletons for the upper limbs are given much focus due to their contribution with regaining control in activities of daily-living (ADL). Current methodologies in anthropomorphic product design simplifies the complex requirements of the human anatomy (Xu and Todorov, 2016), which may be detrimental to the user because their comfort and safety as an injured patient may be compromised.

When a person undergoes physical therapy, a therapist or physician assists the patient in performing exercises to regain range-of-motion and perform activities of daily living. With the aid of a robotic exoskeleton, the patient can perform a more accurate trajectory. However, there are instances where the system is not compatible with the user. A proposed solution is to perform a user-centric design methodology by reviewing existing devices in rehabilitation robotics and enumerating the requirements and gaps that need to be addressed. As discussed by Ulrich and Eppinger (2012), it is important to consider the user needs and requirements of a device early in its conceptual design phase to prevent the loss of compatibility with its user.

In this study, user needs were considered to be the central contributing factor in the design of an upper limb exoskeleton (ULE) for neurorehabilitation. In the next sections, a review of existing designs and their corresponding features are presented. This extensive list paved the way to the qualitative assessment of user needs and upon which importance ratings from a consensus of both engineering and clinical perspectives were given. The results of this analysis were then used in the development of a 7-degree-of-freedom (DOF) wearable robot for Filipino and Asian patients post-stroke and other CNS injuries; an approach that enables developers to have prior knowledge of existing design problems and use it to incorporate user-centricity and compatibility with their current design.

2. REVIEW OF RELATED LITERATURE

A number of studies have already presented reviews on the designs of exisitng robot-assisted devices for rehabilitation (Maciejasz et al., 2014; Chang and Kim, 2013; Gopura et al., 2011; Gupta and O'Malley, 2007). While rehabilitation robotics is an extensive field, mechanical designs for ULE follows a model that aggrees on the orientation of robotic joints and their alignment with the body. A 7-DOF model of the upper limb was found to be the most common configuration. This accounts for 3-DOF in the shoulder (abduction-adduction, flexion-extension and shoulder rotation), 2-DOF in the elbow (flexion-extension and pronation-supination), and 2-DOF in the wrist (flexion-extension and radial-ulnar deviation). In other designs, the mobility of the back was increased by 1-DOF, accounting for scapular displacement as such in the case of Liszka (2006). Nevertheless, variations in the design features particular to its wearability and physical interactions with the body are found to be more prominent in most devices. A previous study by Baniqued et al. (2015) highlighted the design considerations concerning the wearability of ULE for neurorehabilitation.

Since the objective of this study is to arrive with an improved design for a 7-DOF ULE, the review of existing devices shall be exclusive to those that have similar mobility and kinematics with the current device. This allows the developers to focus on the best design features concerning the wearability and physical interaction of the ULE device. Table 1 presents a summary of exisiting devices that passed this exclusion criteria.

Table 1. Existing ULE Designs

Developer/s	Name	Prominent Features
Pons et al., 2007	WOTAS	• Specialized applications • Use of straps for attachments
Hocoma, 2012	ArmeoSpring	• Provision for hand grips • Arm weight support • Easy to operate • Accessible
Vitello et al., 2012	NeuroExos	• Fits the shape of the user limb segments • Comfortable
Perry et al., 2007	CADEN-7	• Kinematic compatibility • Prevent excessive velocity and torque
Stein et al., 2007	MyoPro	• Portable • Adjustable • Robust
Roderick and Carignan, 2005	MGA Exoskeleton	• Prevent excessive velocity and torque • Detection of anomaly
Jackson et al., 2013	iPAM	• Feedback and assessment • Gamification of exercises

The aforementioned devices were evaluated based on both the positive and negative impact of their prominent design features with the user requirements. This shall be the basis of the user needs assessment performed in the next section of this paper.

For a ULE to be compatible with the Filipino and Asian body types, their anthropometric measurements must also be considered. Table 2 shows a summary of anthropometric measurements of the Filipino body type obtained from workers in the manufacturing industry (Del Prado-Lu, 2007). The measurements presented were taken and considered from a standing position because they directly affect the intended design of the exoskeleton. These measurements shall be used to account for the linkages that connect the joints of the intended ULE.

Table 2. Median Anthropometric Measurements of Filipino Workers (Del Prado-Lu, 2007)

Measurement	Male (cm)	Female (cm)
Standing height	167.00	155.00
Shoulder height	137.00	127.00
Shoulder width	44.00	40.00
Shoulder-elbow length	33.00	31.00
Length of upper arm	26.00	25.00
Length of lower arm	25.00	24.00
Upper reach	190.00	191.00
Overhead fingertip reach	213.00	196.00
Arm span	169.00	153.00
Shoulder Circumference	96.00	95.00
Biceps circumference	27.50	25.00
Lower arm circumference	25.00	22.00
Forward reach	78.00	70.00
Hand length	17.82	18.00

3. METHODOLOGY

3.1 User Needs Analysis

A qualitative analysis of the user requirements for a 7-DOF ULE was performed. This methodology was a method developed by Ulrich and Eppinger (2012) which accounts for existing design problems and issues with the current devices discussed in Section 2. Upon review of the prominent design features of the current devices, a preliminary list of user requirements were presented to the design engineers and their medical collaborators. For this study, the users were classified into two (2): patients and therapists/physicians. Doctors from the Department of Rehabilitation Medicine of the Philippine General Hospital (PGH) were asked to provide insights to the needs of the intended users of the product. An observership session was also done involving researchers and actual stroke patients assisted by PGH doctors during therapy.

Furthermore, PGH doctors led by Dr. Jose Alvin Mojica (Department Chair) and Dr. Christopher Constantino (3rd Year Resident) also shared their experiences and pain points during an interview.

3.2 Importance Ratings

The results of the review of exisitng designs and the interviews performed with the medical collaborators from PGH have arrived with a final list of user requirements for a 7-DOF ULE for neurorehabilitation. From this list, both the design engineers (3) and medical collaborators (3) have assigned importance ratings (1-5 with 5 being the most important) to each user need. After which, a design sprint discussion was performed to arrive with a consensus of the final importance ratings. This approach determines which features are of most important for the user and allows the device developers to choose between the trade-offs presented for each design category.

3.3 Development of a 7-DOF ULE Prototype

Finally, the results of the user needs analysis and their corresponding importance ratings were used as the basis for the final design features and technical specifications of the intended 7-DOF ULE. A mechanical design of the device was generated using the computer-aided design (CAD) software CATIA and was 3D printed in polylactic acid (PLA) material using a Makerbot z18 Replicator 3D printer. Brushless DC motors connected to an Arduino Mega microcontroller were used to actuate the exoskeleton while a surface electromyography (sEMG) sensor was installed to receive biofeedback. The developed prototype was then presented to the medical collaborators for another round of evaluation and iteration until both parties are satisfied with the design and have approved it as fit for fabrication and assembly.

4. RESULTS AND DISCUSSION

4.1 User Needs Analysis and Importance Ratings

Table 3 shows the results of the combined evaluation in the review of existing ULE designs and the discussion with the rehabilitation doctors from PGH. The discussions lead to the enumeration of fifteen user needs and the consensus of assigning importance ratings from both the design engineers and medical collaborators.

Table 3. User Needs Analysis

No.	User Needs (The robotic exoskeleton…)	Importance Ratings*
1	is easy to operate	4
2	provides handgrips for grasping	3
3	feels comfortable when executing various movements	4
4	can hold and support the whole weight of the arm	5
5	fits the shape of the limb segments	4
6	has compatibility with the joint kinematics of the user	5
7	can accommodate various physical shapes and sizes	4
8	works with a variety of users and injury cases	3
9	provides straps for the attachments	4
10	does not hinder the patient's residual control	4
11	can be used repeatedly for a long period of time	3
12	does not move the patient at excessive velocities	5
13	does not apply excessive torque	4
14	is cost-efficient and affordable	3
15	is portable and easily accessed	4

* 5 – Very Important, 4 – Important, 3 – Neutral, 2 – Less Important, 1 – Least Important

The user requirements that were considered to be very important, receiving an importance rating of 5, were related to the mechanical design, safety features and kinematics of the device. While those that have received an importance rating of 4 were related to its wearability. The results of the user needs analysis provided insight to the priorities of both engineering and clinical researchers in the design of a ULE with consideration to the requirements of its users. The next step was to translate the user needs into a technical specifications matrix. Table 4 presents a list of product specifications and the relative user requirement that it addresses (related to Table 3).

Table 4. Product Specifications

Design Features and Specifications	User Needs Addressed
Provide an uncomplicated setup using less components as possible	1, 8, 15
Provide soft and comfortable handgrips	2, 3
Use soft and smooth interfaces for the skin	3, 11
Motors are programmed for smooth movement	3, 12
Provide soft shells in contour with the arm attachments	3, 5, 11
7-DOF model exoskeleton with forward kinematics in parallel with the upper limbs	4, 6, 7, 8, 12, 13
Provide adjustable arm links	6, 7, 8
The straps and attachments are made of flexible materials	3, 9, 10
Use backdrivable DC brushless motors	8, 10, 13
Use robust and reliable components	4, 14, 15
Optimum actuator control using Arduino	1, 10, 11, 12, 13
Make linkages detachable	8, 14, 15

4.2 Development of a 7-DOF ULE Prototype

Upon generating a list of product specifications, a mechanical design of a 7-DOF ULE for neurorehabilitation was generated using the CAD software CATIA. A rapid prototype was fabricated via the 3D printing of individual links and the assembly of mechanical, electronic and software components. Figure 1 highlights some of the physical design features from the user needs analysis (i.e. soft comfortable handgrips, adjustable and detachable arm links) reflected to the 3D-printed ULE device.

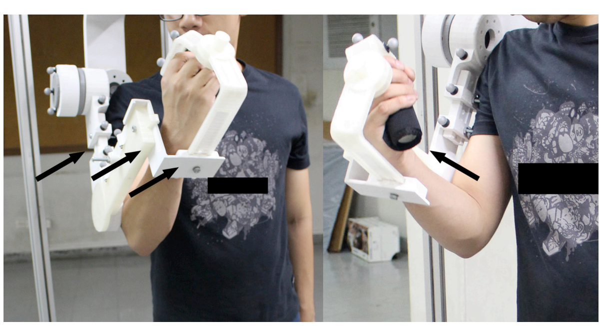

Fig. 1. Design Features of the 7-DOF ULE based on User Needs Analysis

The 3D-printed ULE prototype was presented to the medical collaborators at PGH. According to their observations, the wearable robotic exoskeleton can perform the acceptable range of motion of the upper limb and can be applied to both physical therapy and occupational therapy exercises in neurorehabilitation. The attachment interfacing the human skin satisfies the comfortability when accomodating the excess weight of the patients who have lost control of the full arm.

5. CONCLUSION

This study was successful in demonstrating how the assessment of user needs participate in the design of a 7-DOF wearable robotic exoskeleton for neurorehabilitation. Review of existing devices in literature and their corresponding design issues have been beneficial to the developers in arriving with a list of user requirements. After a number of discussions, observership sessions and design sprints with rehabilitation doctors from the Philippine General Hospital, importance ratings for each user need were assigned. This lead to the generation of a technical specifications matrix and was eventually reflected in a 3D-printed prototype of the device.

Performing an analysis of user needs early in the design process provides an essential approach in the product development of biomedical devices. By focusing on the user needs, design engineers can lessen the lag time in the conceptual design stage and create clinically-significant technologies that will both benefit the patient and their therapists.

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