INTERNATIONAL DESIGN CONFERENCE - DESIGN 2014
Dubrovnik - Croatia, May 19 - 22, 2014.

IDENTIFYING DESIGN OPPORTUNITY SPACES IN NEW USER INTERFACES FOR EXOSKELETON MOBILITY DEVICES

E. Kim, Y. J. Jeong, K. Mock, V. Stanton Kocsik and A. M. Agogino

Keywords: human-centered design, UI design, exoskeletons, personas, opportunity spaces

1. Introduction

1.1 Why use human-centered design for exoskeleton UI development?

Human-centered design is an innovation and design philosophy that emphasizes an understanding of the needs, attitudes, behaviours, and goals of the user [Gasson 2003]. Its systematic user research methodologies have been broadly adopted in new product/service development processes to make new offerings more useful and attractive to customers/users. The human-centered design process helps designers better understand human behaviour and how people engage with products and services. [Krippendorff 2004]. One human-centered design methodology – the creation and use of archetypal personas that represent important classes of users – provides a clear way to define target users who share common desires, goals, and behaviours, and who will benefit from the new design concepts [Cooper 1999], [Grudin and Pruitt 2002], [Pruitt and Adlin 2006], [Cooper et al. 2007]. Another methodology, the 2x2 framing matrix, allows designers to synthesize data gathered during interviews, observations, and user tests and in order to visualize opportunity spaces for future application areas [Lowy and Hood 2004]. In this paper, we identify design opportunity spaces in user interfaces for exoskeleton devices based on human-centered design processes. Although there are a number of researchers in the field of exoskeleton technologies for human augmentation, human-centered design methodologies have not yet been applied in developing these devices. Since this human augmentation technology is near reaching maturity and affecting peoples' lives outside of research laboratories, such as for paralyzed patients or soldiers, exoskeleton design has the opportunity to move beyond its initial technology-driven approaches to include design strategies based on human-centered design methods. Although exoskeleton technologies include a broad range of approaches, here we focus our study on the user interface (UI) design to control exoskeleton devices – the medium of interaction between machines and human users.

1.2 History and overview of exoskeleton technology

Research in human exoskeleton devices began in the 1960s, mainly for developing two different technologies: 1) devices to augment the abilities of able-bodied humans, often for military purposes, 2) devices to assist ambulation for physically challenged persons. Although originally created for these two distinct applications, a number of research groups have nearly accomplished maturity of exoskeleton technology in commercialized products covering various applications, and wider user segments. For assistive purposes, Rex and ReWalk™ are currently available on the market for clinical use in rehabilitation centers. Patients with strokes, spinal cord injuries, and other injuries causing mobility disorders can potentially benefit from these technologies: rehabilitation out of their wheelchairs, achieving independence in their daily life and overcoming secondary injuries due to prolonged sitting in wheelchairs. These medical robotic exoskeletons have pre-programmed, powered actuators at the joints, aligned to the wearer's biological joints to mimic natural human gait, while providing some rigidity to support the patient's body, with or without the help of external walking aids. The detailed design of these devices can be found at [Goffer 2002], [Zeilig 2002], [Little 2009], [Strausser 2011], [Kazerooni 2011]. For augmenting the abilities of able-bodied persons, the Berkeley Robotics & Human Engineering Lab has developed the Berkeley Lower Extremity Exoskeleton (Bleex) [Amundson et al. 2005], [Chu et al. 2005], [Zoss et al. 2006] and the Human Universal Load Carrier (HULC™) [Lockheed Martin 2009]. These devices also have pre-programmed, powered actuators aligned with the wearer's biological joints. However, the actuators are used to amplify the wearer's movement when the user's intent of movement in a certain direction is detected, thus reducing the metabolic cost used in the movement. The detailed design of these devices can be found in [Zoss and Kazerooni 2006].

1.3 Overview of exoskeleton UI

These aforementioned exoskeleton robots have two varieties of user input receiving systems: 1) sensing user intent from the wearer's posture using a variety of sensors and 2) receiving explicit commands from the wearer via a "controller," such as a joystick or buttons. The first method appears to be more beneficial for able-bodied wearers as it requires minimal effort from the user to issue commands. However, it causes a potential risk for persons with mobility disorders; these users' limited mobility and muscle control can cause a misinterpretation of the operator's posture, which could cause the exoskeleton and user to fall. Exoskeletons with explicit UIs, such as the systems used in Rex, require more user effort in commanding steps via joysticks or buttons; however, this appears to minimize the risk of mistriggering due to the pilot's weakened motor control caused by their injuries.

2. Research methodologies

Applying a human-centered design process [Dym et al. 2005], [Beckman and Barry 2007], we focus on a broad range of exoskeleton device applications, outside of those currently being considered in research laboratories today. Our research has been framed to discover new innovation spaces by creating new concepts of user interfaces for exoskeleton devices.
Our primary research questions are:

- What are the most critical mobility needs of patients with mobility disabilities?
- Where are new opportunity spaces for exoskeleton UI applications?
- What are the most suitable UI concepts for exoskeleton devices for different purposes – medical, military, entertainment, etc.?
- What are the recommended UI concepts for patients with different levels of injuries?

2.1 Personas

We used a combination of pre-testing, observations, interviews, surveys, and usability tests for our human-centered design research. Due to limited access to our target user segments of individuals with physical disabilities, the number of interviews was relatively small (eight), which made our team focus on the synthesis and integration of a smaller sample of in-depth, rich data coupled with secondary and tertiary ergonomic data from previous research [Schiele 2009], [Wehner et al. 2009], [Swift et al. 2010]. Personas (user archetypes) were used to capture the major needs associated with categories of mobility goals and task scenarios. Personas have been found to provide a clear way to define target users who share common desires, goals, and behaviours, and who will benefit from the new design concepts [Cooper 1999], [Grudin and Pruitt 2002], [Pruitt and Adlin 2006], [Cooper et al. 2007]. In addition to "strengthening the focus on the end user, their task, goals and motivations", Long [2009] found that personas can also effectively improve communication between team members with a more constructive focus on usability issues.

2.2 Framing opportunity spaces

2x2 framing matrices were used to synthesize data gathered during interviews, observations, and user tests and in order to visualize opportunity spaces for future application areas [Lowy and Hood 2004]. Critical dimensions considered in the framing were level of physical ability, degree of UI operation required and implicit versus explicit control. The degree of maturity of the UI technology was also considered. In the following sections, we describe four categories of primary user needs, create and frame 40 new UI concepts, and finally, describe some of the most compelling concepts, one concept for each persona developed.

3. Results

3.1 Summary of interviews, observations, and user tests

Our data were collected from pre-testing, observations, interviews, and user tests in order to understand the user's general references on exoskeleton UIs and their level of physical strength. The pre-testing and observations were performed on seven medical exoskeleton test pilots at the Robotics and Human Engineering Laboratory at UC Berkeley. We conducted user tests, in-depth interviews, and surveys with eight subjects on our target user segment at participants' offices and the Ed Roberts Campus and the Center for Independent Living in Berkeley, CA. Archetypal personas are created to provide an explicit way to define our target users, which are described in the following section.

3.2 Archetypal personas

Four personas are developed based on individuals interviewed in each of the four user categories: Crutch users, Wheelchair users, Powered Wheelchair users and Military Soldiers. Each persona represents one segment of the possible user segments of individuals with mobility disabilities. The level of physical ability is scored on a 0-5 scale with 0 being the lowest and 5 the highest. Table 1 summarizes four archetypal personas with key attributes that describe who they are.

3.2.1 Samuel, crutch user

Samuel is a 23-year-old male undergraduate student who lives in the San Francisco Bay Area. He has been using a crutch for the last 3 years. He possesses enough strength in his upper body and fingers to perform ordinary functions, even though his lower body has low strength. Additionally, he shows strong motivation to use a medical exoskeleton to walk again, since he only recently lost this ability.

3.2.2 Jennifer, wheelchair user

Jennifer is a 31-year-old female living in Berkeley. Born with a degenerative disease, she has spent the majority of her life in a wheelchair. In order to operate an exoskeleton advice, Jennifer would need to use a walker or crutches. She wears gloves almost every day to keep her hands clean while using her wheelchair, but must replace her gloves every two to three weeks because they quickly wear out. She sees great benefit from a better user interface for operating an exoskeleton device.

3.2.3 Kevin, powered wheelchair user

Kevin is quadriplegic and a lifelong powered wheelchair user. His disability precludes use of an exoskeleton device since his condition has rendered him unable to user his upper body muscles at all. Not only that, but the fact that he has been a lifelong powered wheelchair user makes Kevin reluctant to try a new device, which has the latent risk of falling down and malfunctioning, a worry compounded by his very weak body. Kevin represents a potential user in the future, when the project has moved out of the R&D phase, and exoskeletons have improved in safety, stability, and reliability.

3.2.4 Andrew, military soldier

Andrew is a 25-year-old male from Boston who serves in Afghanistan as a Sargent with the U.S. Army Infantry, where he leads a team of soldiers at an outpost. On patrol at least once a week, he carries his helmet, body armor, weapons, ammunition, ancillary equipment, and enough food and water to last the expected duration of the action. Longer patrols require additional equipment and a second pack, giving him a fighting load of 60 to 70 pounds, and a marching load that can exceed 100 pounds. The weight is exhausting in high temperatures, leaving him fatigued when he arrives at a target. Andrew feels that his load impedes his mobility and agility, and places him at risk of injury when traversing uneven terrain. He also helps his troop with the logistics of moving equipment and supplies, tasks that involve repetitive high lifting. With these various activities, Andrew is prone to suffering from lower back pain, knee injuries, and foot blisters. His strength, augmented by an assistive device, could prevent injury and reinjury, allowing him more active time in the field.

Table 1. Four archetypal personas

Personas	***Samuel***	***Jennifer***	***Kevin***	***Andrew***
Type	Crutch User	Manual Wheelchair User	Powered Wheelchair User (Quadriplegic)	Military Soldier
Bio	• Age: 23 years old • Gender: Male • Region: San Francisco • Years of mobility aid use: 3 years	• Age: 31 years old • Gender: Female • Region: Berkeley • Years of mobility aid use: 24 years	• Age: 42 years old • Gender: Male • Region: Seattle • Years of mobility aid use: Life-long	• Age: 25 years old • Gender: Male • Region: Boston • Years of mobility aid use: N/A
Physical ability	1. Muscle Strength (Upper Body) ●●●●○ 2. Muscle Strength (Lower Body) ●●●○○ 3. UI Operational Capability ●●●●○	1. Muscle Strength (Upper Body) ●●●○○ 2. Muscle Strength (Lower Body) ●●○○○ 3. UI Operational Capability ●●●●○	1. Muscle Strength (Upper Body) ●○○○○ 2. Muscle Strength (Lower Body) ●○○○○ 3. UI Operational Capability ●●●○○	1. Muscle Strength (Upper Body) ●●●●● 2. Muscle Strength (Lower Body) ●●●●● 3. UI Operational Capability ●●●●●
Quote	*"I really hope I can walk again someday on my own."*	*"It would be wonderful to use my device without having to ask my aide for help every moment"*	*"I'm a little scared that this thing will be stable enough to hold me up, especially if I start to tip over"*	*"Even with frequent training, exercise and conditioning, my duties are exhausting and dangerous. Any tool that can help will be great."*

4. Data synthesis and frameworks

With the data gathered from pre-testing, observations, interviews, user tests, and the personas, this study presents the following human-centered design methods: user needs analysis, brainstorming, concept generation, and 2x2 framing matrices. The data, such as interviewee's responses and interpretation of observations, were coded into meaningful categories for the next phase of data synthesis and frameworking. Prior to the data synthesis, each research team member generated ten ideas using a half-sheet to describe a title, concept description, and list of primary features and attributes for each unique idea. Using a "round robin" style of discussion, each team member had a chance to explain his or her ideas and discuss them with the team. This section defines primary user needs, clusters new UI concepts, and identifies opportunity spaces for new exoskeleton UI designs based on the data obtained.

4.1 Defining primary user needs

We determine four broad categories of user needs based on synthesis and analysis of data gathered from the design processes previously described. These user needs are categorized into four broad headings: intuitiveness, information feedback, comfort, and independence.

4.1.1 Intuitiveness

The interface should be easy to learn, easy to calibrate, and easy to use. The exoskeleton UI operation should be completely natural, and allow fluid transitions between movements.

- Natural movement
- Learnability

4.1.2 Information feedback

Unlike the closed-loop nervous system of the human body, exoskeletons are external and artificial. The exoskeleton should provide information feedback, as the nervous system does. Otherwise, the user cannot perceive their own motion, position, sense the amount of force, feel pressure, sense location or establish orientation with respect to gravity in order to maintain balance. For safety, the user should be able to maintain full control over the motion of their exoskeleton. Any deviation from the expected natural movement of the body may destabilize balance or, over a longer term, cause problems with posture or the musculo-skeletal system.

- Controllability
- Safety
- Reliability
- Protection

4.1.3 Comfort

The physical interface should be comfortable and suitable for the body. It should comply with the existing body shape, skeletal structure, and skin conditions of the user.

- Formfitting
- Lightweight
- Compact
- Weather-proof
- Breathable

4.1.4 Independence

Use of the exoskeleton in daily life should not require an auxiliary individual to help the user put it on or set it up. The exoskeleton should not inhibit the daily activities of the user.

- Minimal interference with other physical movements
- Ease of don and doff
- Operable by user alone

4.2 Categorizing UI concepts

Next, the research team generated UI concepts. The previously determined user needs are kept in mind while generating ideas. A total of 40 UI concepts are developed, ten for each specific target user segment (Table 2). For each concept, a title, description, list of primary features and attributes, and a metaphor are documented to fully describe the design ideas.

Table 2. Forty UI concepts developed (duplicated concepts are merged into similar categories)

Explicit UI		Implicit UI
• Remote Controller • Wheel Remote • Pushbutton UI on Crutch Handles • Step Grip • Remote with Buttons • Rotating Wheel • Breath-Powered • Joystick UI • Wheel Controller • Trackball • Motion Sensor • Mobile App • Steering Trackpad • Touch Screen/Swipe Pad • Voice Command Activation	• Glove UI Exo-Controller • Piezoelectric Glove • Lap Remote • Tangible Remote Gyro Controller • Palm Sphere • Segway like Mobile Wheel • Sleeve Receptors • Muscle Contraction Sleeve • Wearable Glasses Controller • Smart Watch Controller • Glove UI with Monitoring Display • Tongue Control • Wand Controller	• Ankle Bracelet • Torso Angle Sensor • Motion Vest • Motion Bracelet • Arm Muscle Activation • Shoe Sensors • Mind-Powered Headwear • Brain-Powered Controller

Then, the concepts are categorized according to various criteria. In one categorization method, the UI concepts are sorted according to the location on the human body from which they were actuated; for example, a UI controlled by the fingertips, or a UI controlled by the mouth. Figure 1 shows a breakdown of the locations on the human body on which the concepts fell (b), as well as a grouping of external UI devices (a), which are not located on the body itself.

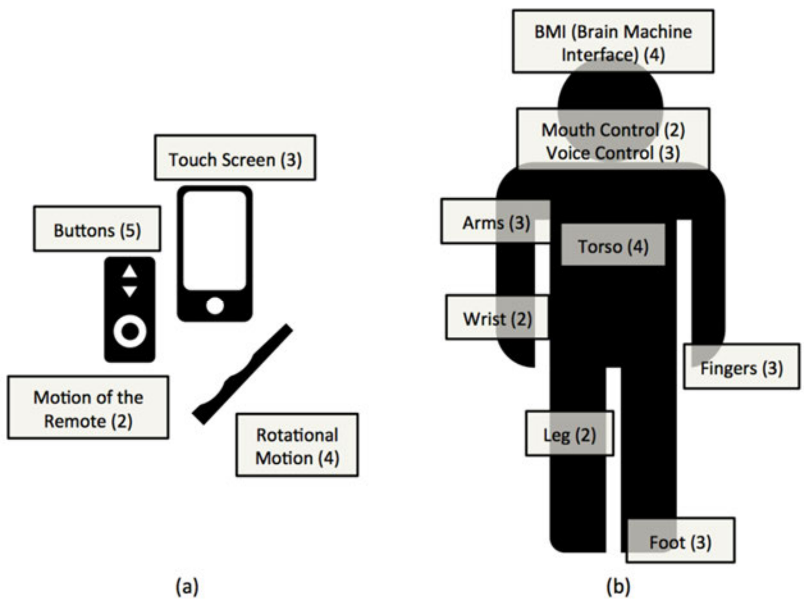

Figure 1. New UI concepts generated, (number of ideas developed): (a) External UI device concepts (14); (b) User coupled UI concepts (26)

4.3 Creating 2x2 opportunity spaces

Based on our descriptive data analysis, the four personas created earlier are mapped onto a 2x2 matrix against the severity of injuries and the UI operation level. Figure 2 describes where each persona sits on the four quadrants showing 1) the relative levels of physical ability on the x-axis – i.e., the physically challenged lie on the left hand side, whereas the able-bodied stand on the right hand side; 2) UI operation level on the y-axis – i.e. the user's ability of UI operation.

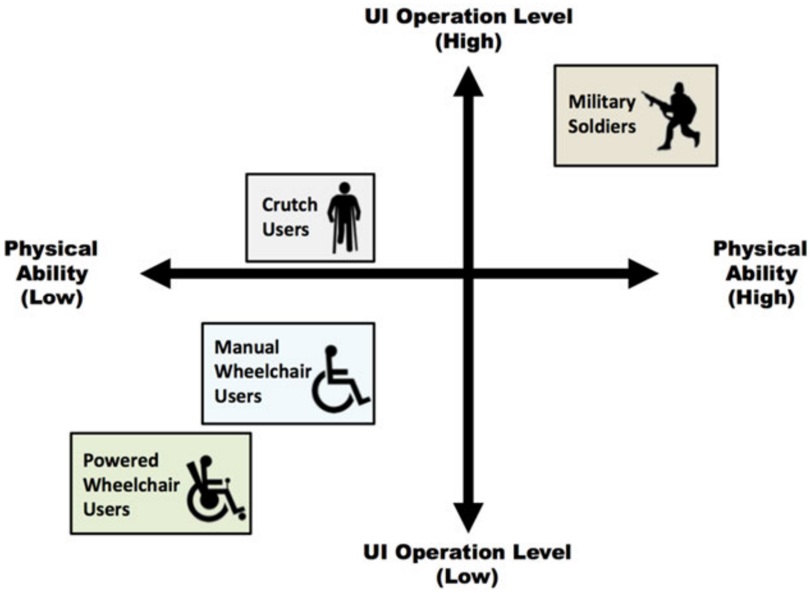

Figure 2. Personas mapped by the level of physical ability (High/Low) and UI operation level (High/Low)

While coupling the UI concepts with their body location provides one way of visualizing our concepts in Figure 1, the concepts are re-grouped and plotted according to additional categorizations (Figure 3); with one axis describing how developed the critical technology is currently, and the other describing whether the UI is activated explicitly (e.g., the user presses a button) or implicitly (e.g., a device senses the user's muscle activation). The diameter of each circle in Figure 3 represents the number of concepts in each concept cluster.

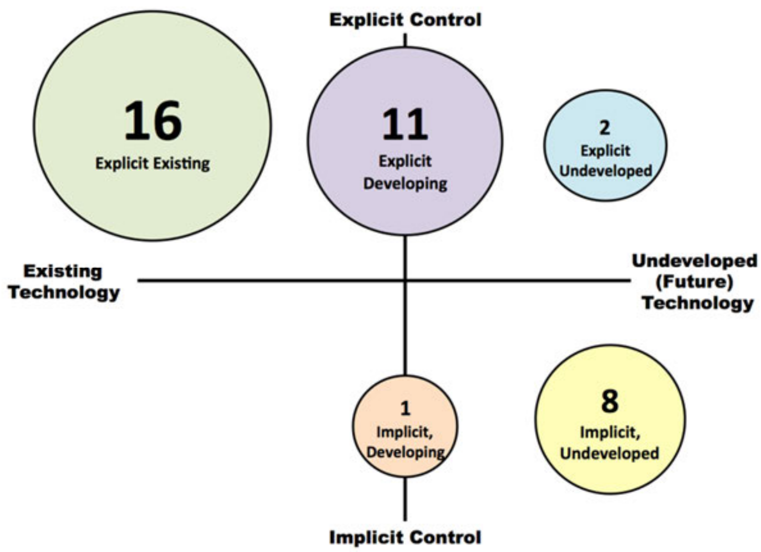

Figure 3. Number of new UI concepts generated mapped by the degree of explicitly or implicitly and the degree of the necessary technology's development

5. Most compelling concepts for archetypal personas

The 40 UI concepts are mapped with each of the four user personas in Figure 2 in order to determine the most compelling concepts to aid each different type of exoskeleton user. Throughout the internal concept scoring, we used a 0-5 scale with 0 being the lowest and 5 the highest, with the criteria based on the primary user needs: intuitiveness, information feedback, comfort, and independence. The most compelling UI concept for each type of archetypal persona is selected and explored in-depth as per our recommendation (Figure 4).

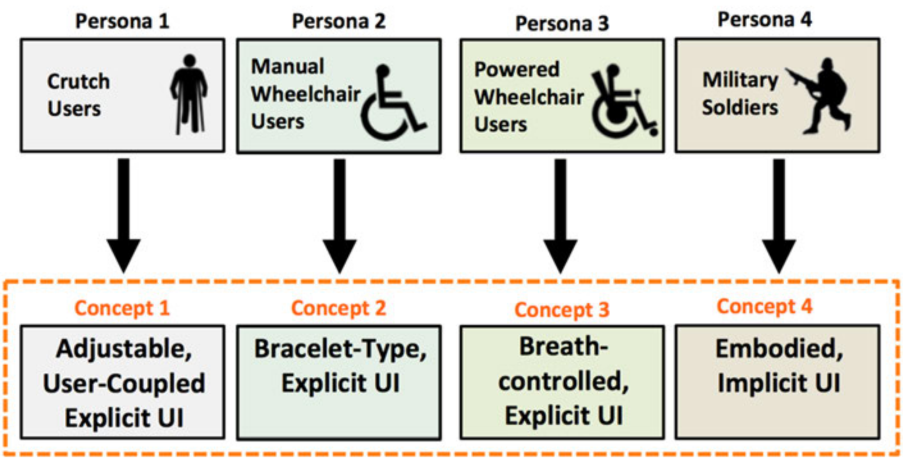

Figure 4. Creation of four most compelling concepts; one UI concept for each type of archetypal persona

5.1 Adjustable, user-coupled explicit UI for persona 1 (Samuel, crutch user)

Samuel has been a crutch user for three years, and he has enough physical strength in his upper body to operate more complex UI's. He is more willing to try new UI concepts if they can provide him with a compelling experience that is better than his current crutch system. For this type of user, the top user needs are independence and comfort. To satisfy Samuel's needs, we suggest implementing exploratory and user-coupled UIs such as a vest worn on the torso that measures the angle of the user's upper body and triggers appropriate motion, such as stepping forward or stopping. Another possibility is to implement a remote UI into the user's mobile phone device, which could allow finer control of the exoskeleton and provide customizable interface design: for example, adjusting gaits speeds, length, sounds feedback, etc.

5.2 Bracelet-type, explicit UI for persona 2 (Jennifer, manual wheelchair user)

As a manual wheelchair user, Jennifer's main needs in an exoskeleton user interface are also comfort and independence, although she expects to achieve a lower level of independence than Samuel is able to. Intuitiveness and information feedback may be of lesser consequence, as she retains function and feeling in her upper body similar to that of a healthy user. Jennifer possesses a wide range of motion in her upper body and greater muscle strength, granting her a level of independence not afforded to a paraplegic, or powered wheelchair user. However, with limited mobility in her lower extremities, Jennifer's primary mode of interaction with the UI must engage the upper body. To meet Jennifer's needs in an upright exoskeleton device, we propose a bracelet UI. Worn on the wrist, a bracelet UI is largely hands-free, unobtrusive, and does not require another person's assistance to use on a daily basis. It may allow the user to take advantage of the arm swinging motion that occurs naturally in healthy users when walking without an assistive device. A bracelet UI could detect motion in the arms and use the direction and degree of rotation to control movement in the legs. Users similar to Jennifer would also benefit from UIs satisfying the same needs for comfort and independence. Since the strength of manual wheelchair users lies predominantly in the upper body, UIs that accommodate this without compromising the user's existing level of independence are most suitable. For example, a UI worn as a sleeve may sense muscle activity in the user's arms and translate that into an action. In addition to the wrist and arm, other relevant concepts fall in the areas of the torso, hand, and fingers.

5.3 Breath-controlled, explicit UI for persona 3 (Kevin, powered wheelchair user)

Kevin is a quadriplegic, paralyzed from the neck down. Unlike our other personas, he is extremely limited in UI options, since he has muscular control of just his head and neck. The user needs most important to Kevin are therefore a reliable information feedback system and intuitiveness. Since he cannot use his hands, legs, or arms at all, we focused on UI concepts controlled by the mouth or brain. We propose a breath-powered exoskeleton UI control for severely injured people like Kevin. This technology, referred to as "sip-and-puff," currently exists for powered wheelchair users with extreme disabilities. With a breath-powered UI, the user can perform a number of commands: a hard puff out, a hard sip in, or a continuous soft sip or puff, corresponding with functions such as starting and stopping in the forward direction, starting and stopping in the backwards direction, or turning left and right. In addition to being an established technology, this UI provides strong information feedback to Kevin, by responding in a safe, reliable, and precise manner. The system is relatively simple, allowing Kevin to go about his daily activities without needing to operate a complex UI or worrying about the system misinterpreting his commands. It is also intuitive, as Kevin does not need to use his hands. Finally, this UI allows Kevin a degree of independence to move around under his own volition. Alternate UI concepts explored for Kevin include a voice-activated or a brain-powered UI.

5.4 Embodied, implicit UI for persona 4 (Andrew, military soldier)

Andrew Lee is a soldier whose job requires running with heavy loads. For Andrew, the exoskeleton aims to enhance his physical strength and agility. In this case, the most important user needs for Andrew's military exoskeleton are intuitiveness and information feedback. Andrew does not want to "think" how to use the exoskeleton, but he would prefer that the machine detects his intention fast enough to augment his movements by itself. Receiving information feedback, such as the exoskeleton's remaining battery life, and other possible add-on features for soldiers (time, maps, etc.) would also be very useful for him. Regarding these factors, an implicit, embodied UI with sensors detecting user intent would be the most ideal UI for Andrew. Voice control combined with an eyeglasses type of interface to receive other information would be suitable for Andrew's needs.

6. Discussion and reflection

Current applications of exoskeletons – medical, military, and multipurpose – have previously been discussed by other researchers. However, the scope of research has been limited mostly to the design and functionality of exoskeletons in specific uses [Dollar and Hurr 2008], [Mikolajewsja and Mikolajewski 2011]. As human augmentation technology becomes more accessible, especially in the form of aid to the injured, exoskeleton UI will be critical to the degree to which an exoskeleton device integrates into a user's life. Our four recommendations can better facilitate this integration with users' varying degrees of ability, as opposed to the conventional "one size fits all" approach. Identifying the primary target groups and figuring out their key needs were the priorities of this study in order to broaden the application of mobile exoskeleton devices beyond research labs with targeted user populations. The biggest concern with our research project was the limited access to various types of users. Our eight interviewees were drawn from those working with the Berkeley Robotics and Human Engineering Lab and the Ed Roberts Campus for the disabled in Berkeley, California. Even with this small number, we were able to find distinct user needs and physical conditions and preferences. However, the authors recognize the need to further increase the number of test subjects, as well as the variety of prototypes. Another challenge was the need to tightly coordinate the research methodologies used within the research team. Personas and 2x2 matrices, well-structured design research methodologies, provided not only a clear way to define target users, goals, and behaviors, but also promoted active communication between research team members.

7. Conclusions and future work

The goal of our research was to identify design opportunity spaces and propose UI concepts for the next generation of exoskeleton devices. We defined the most critical mobility needs of users with four broad headings: intuitiveness, information feedback, comfort, and independence. The design team found that the use of personas helped us focus on the top mobility needs associated with each persona archetype. With the data gathered from pre-testing, observations, interviews, user tests, and the personas we created, we developed 40 UI concepts and mapped them to 2x2 framing matrices.

Mapping of these concepts on the human body and external UI devices helped us to understand new opportunity spaces beyond just the traditional interaction between the user's hands and relevant machines. Finally, we proposed examples of compelling UI concepts, one example concept for each persona created; Adjustable and User-Coupled Explicit UI for Persona 1 (crutch users), Bracelet-Type and Explicit UI for Persona 2 (manual wheelchair users), Breath-controlled and Explicit UI for Persona 3 (powered wheelchair users), and Embodied and Implicit UI for Persona 4 (military soldiers). In the future, we plan on further expanding the size, range and type of user research, which will serve to broaden our concept generation. We will implement the most promising UI concepts into higher fidelity prototypes, followed by concept/user testing with potential users. We also plan to investigate the role that emerging technologies in soft robotics can contribute to UI concepts for exoskeleton mobility devices [Paik 2013], [Sabelhaus et al. 2014].

Acknowledgement

The authors would like to express their sincere gratitude to the research subjects who participated interviews, user tests and provided invaluable feedback. Finally, the authors would like to acknowledge the Berkeley Robotics and Human Engineering Lab and Berkeley Energy and Sustainable Technologies Lab in the Mechanical Engineering department at UC Berkeley.

References

Amundson, K., Raade, J., Harding, N., Kazerooni, H., "Hybrid hydraulic-electric power unit for field and service robots", in Proc. 2005 Int. Conf. Intell. Robots Syst., 2005, pp. 3453–3458.

Beckman, S. L., Barry, M., "Innovation as a Learning Process: Embedding Design Thinking". California Management Review , Vol. 50 No. 1., 2007, pp. 25-56.

Chu, A., Kazerooni, H., Zoss, A., "On the biomimetic design of the Berkeley Lower Extremity Exoskeleton (BLEEX)", in Proc. IEEE Int. Conf. Robot. Autom., Barcelona, Spain, 2005, pp. 4345–4352.

Cooper, A., "The inmates are running the asylum", Macmillan, 1999.

Cooper, A., Reimann, R., Cronin, D., "About Face 3: The Essentials of Interaction Design". Indianapolis, IN: Wiley, 2007.

Dollar, A., Hurr, H., "Lower Extremity Exoskeletons and Active Orthoses: Challenges and State-of-the-Art", in Robotics, IEEE Transactions on Vol. 24, Issue 1, 2008, pp. 144-158.

Dym, C. L., Agogino, A. M., Eris, O., Frey, D. D., Leifer, L. J., "Engineering Design Thinking, Teaching and Learning". Journal of Engineering Education, Vol. 94, No. 1., Jan. 2005, pp. 103-120.

Gasson, S., "Human-centered vs. user-centered approaches to information system design". Journal of Information Technology Theory and Application 5(2):29–46., 2003.

Goffer, A., "Gait-locomotor apparatus", U.S. Patent EP126020119-Feb-2002.

Grudin, J., Pruitt, J., "Personas, participatory design, and product development: An infrastructure for engagement", Proc. PDC 2002, 2002, pp. 144-161.

Kazerooni, H., et al., "Orthesis system and methods for control of exoskeletons", U.S. Patent US20130158445.

Kazerooni, H., Steger, R., "The Berkeley Lower Extremity Exoskeleton", Trans. ASME, J. Dyn. Syst., Meas., Control, vol. 128, Mar. 2006, pp. 14–25.

Krippendorff, K., "Intrinsic motivation and human-centred design", Theoretic Issues in Ergonomics Science, Vol. 5, No, 1, 2004, pp. 43-72.

Little, R., Irving, R., "MOBILITY AID", U.S. Patent WO/2009/08224903-Jul-2009.

Lockheed Martin Unveils Exoskeleton Technology at AUSA Winter Symposium, <http://www.lockheedmartin.com/us/news/press-releases/2009/february/LockheedMartinUnveilsExos.html>, Accessed 3-2014.

Long, F., "Real or Imaginary: The effectiveness of using personas in product design", Proceedings of the Irish Ergonomics Society Annual Conference, <http://www.frontend.com/the-effectiveness-of-using-personas-in-product-design.html>, Accessed 3-2014, 2009, pp. 1-10.

Lowy, A., Hood, P., "The Power of the 2x2 Matrix: Using 2x2 Thinking to Solve Business Problems and Make Better Decisions". San Francisco: Jossey Bass, A Wiley Imprint, 2004, p. 294.

Mikołajewska, E., Mikołajewski, D., "Exoskeletons in Neurological Diseases – Current and Potential Future Applications", Adv Clin Exp Med, 2011, pp. 227–233.

Paik, F., IROS 2013 Workshop on Soft Technologies for Wearable Robotics, <http://rrl.epfl.ch/IROS2013softworkshop>, Accessed 3-2014.

Pruitt, J., Adlin, T., "The persona lifecycle: Keeping people in mind throughout product design". San Francisco: Morgan Kaufmann., 2006.

Sabelhaus, A. P., Caluwaerts, K., Bruce, J., Agogino, A. M., SunSpiral, V., "SUPERball: Modular Hardware for a Mobile Tensegrity Robot", WCSCM6 (6th World Conference on Structural Control and Monitoring), July 15-17, 2014, in press.

Schiele, "Ergonomics of Exoskeletons: Subjective Performance Metrics", in Proc. of the IEEE/RSJ Int. Conf. Intell. Robots Syst., 2009, pp. 480-485.

Strausser K. A., Swift T. A., Zoss A. B., Kazerooni H., Bennett B. C., "Mobile Exoskeleton for Spinal Cord Injury: Development and Testing", ASME Conference Proceedings, vol. 2011, no. 54761, 2011, pp. 419–425.

Swift, T., Strausser, K., Zoss, A., Kazerooni, H., "Control and Experimental Results for Post Stroke Gait Rehabilitation With Prototype Mobile Medical Exoskeleton", in Proc. of the ASME Dyn. Sys. and Control Conf., 2010, pp. 405-411.

Wehner, M., Remple, D., Kazerooni, H., "Lower Extrimity Exoskeleton Reduces Back Forces in Lifting", in Proc. of the ASME Dyn. Sys. and Control Conf., 2009, pp. 49-56.

Zoss, A. B., Kazeroon, H. i, Chu, A., "Biomechanical design of the Berkeley Lower Extremity Exoskeleton (BLEEX)", IEEE/ASME Trans. Mechatronics, vol. 11, no. 2, Apr. 2006, pp. 128–138.

Zoss, A. Kazerooni, H., "Design of an electrically actuated lower extremity exoskeleton", Adv. Robot., vol. 20, no. 9, 2006, pp. 967–988.

Euiyoung Kim, Doctoral Student
Berkeley Energy and Sustainable Technologies Laboratory
University of California Berkeley, Department of Mechacnial Engineering
354 Hearst Memorial Mining Building, Berkeley, CA, USA
Telephone: (+1) 224-795-2839
Email: euiyoungkim@berkeley.edu
URL: http://best.berkeley.edu/drupal