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Design Considerations in Upper Extremity Prostheses

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INTRODUCTION

In 2005 the Defense Advanced Research Projects Agency (DARPA) initiated the "Revolutionizing Prosthetics" program with the goal of dramatically increasing the functionality and capability of upper extremity prosthetic solutions [1]. To support the general goal of restoring near-normal functionality to our wounded servicemembers and other prosthesis users, DARPA particularly focused on increasing the degrees of freedom (DOF) and the capability of the control schemes available to the user. Within the spectrum of research funded as part of the program, our team, led by DEKA Integrated Solutions, was charged with development of a prosthetic arm system that offered dramatic improvements in capability using only non-invasive control schemes.

Mimicking the function of the human arm is a significant engineering challenge. The specifications of the "original equipment" are impressive - 22 degrees of freedom, a vast array of efferent and afferent signals providing actuation, sensation, and feedback/reflexes, combined in a package weighing in at around 7.5 lbs (3.5 kg) and a density of around 1 gm/cm^3 [2,4]. However, advancements in robotic technologies, component miniaturization, manufacturing techniques, microprocessors, sensors, and wireless communications allowed us to develop an advanced upper extremity prosthetic solution.

We employed an iterational, user community-focused design approach for this development effort. Working closely with users, prosthetists, and therapists throughout the process allowed us to capture and quickly implement community feedback. In parallel we focused on solving the difficult engineering problems associated with providing dramatically greater prosthetic arm system capabilities. Where possible, we located our engineering efforts and our clinical studies in the same physical space to facilitate exchanging ideas and rapidly responding to and experiencing the results of our design iterations.

In this paper, we discuss the design approach used for the prosthetic arm system: a general overview of the system characteristics, and a discussion of two specific prosthetic arm system capabilities.

DESIGN CONSIDERATIONS

Our goal was to dramatically expand the capabilities of the prosthesis while enhancing its stability and comfort. Multiple factors needed to be considered in the upper extremity prosthetic design including the arm hardware, control system, power sources, socket interface, and patient control strategies.

The design strategy is schematically represented in Figure 1 and shows the basic elements and pathways for the progression of the design from the first to third generation. Subjective and quantitative data from our engineering team, prosthetists and subjects were analyzed and reviewed before proceeding with the next design iteration.

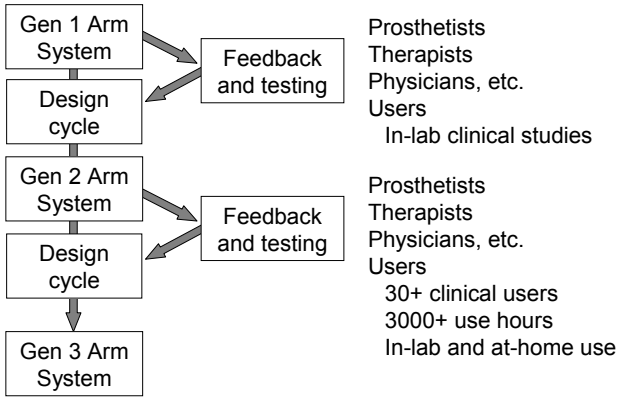

Figure 1. Overall strategy used to advance and prioritize design features through major design iterations.

Our "feedback and testing" process evolved as the design matured. The Gen 1 arm system was used by a smaller set of research subjects over several months. Based on their feedback, substantial improvements were made to the arm system, optimizing the elements of the arm system, the control scheme, and the interface design.

The Gen 2 design was then studied more extensively – increasing the hours of use by research participants, the number of participants, and the environment in which the arm system was used. The Department of Veterans Affairs (VA) established and funded a prosthetic system research team including researchers, prosthetists, and therapists from multiple VA and military centers that joined the clinical study effort. This team brought feedback from a larger set of users, therapists and prosthetists to the engineering team to support the Gen 3 design effort.

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In total, the Gen 2 arm system was used in clinical studies for over 3000 use hours by over 30 users at all configuration levels. Studies were performed at clinical locations at DEKA, Next Step Orthotics and Prosthetics, and the several VA locations. In addition, five study participants were able to take the arm system home for several weeks of use in a non-clinical setting.

The extensive Gen 2 study team provided significant feedback across the entire arm system with insights and suggestions regarding: grip design, joint range of motion; the control system implementation; and the active socket interface. In addition, engineering studies of reliability, capability, and joint use provided additional valuable information incorporated in the Gen 3 design.

GEN 3 SYSTEM OVERVIEW

General features of the modular, fully configured arm (Figure 2) include 10 powered degrees of freedom (DOF), including shoulder abduction-adduction, shoulder flexion-extension, humeral rotation, elbow flexion-extension, wrist rotation, as well as a hybrid motion of wrist flexion-extension and radial-ulnar deviation.

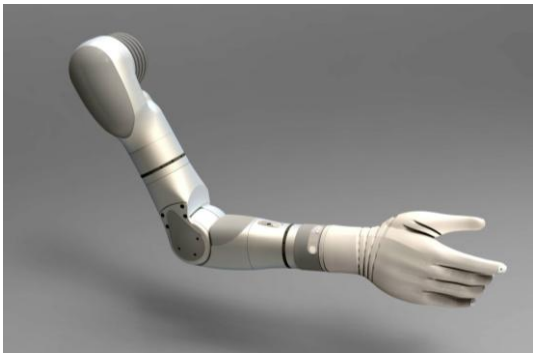

Figure 2. Gen 3 arm shown in a configuration for scapulothoracic (ST) and shoulder disarticulation (SD) amputees (above). Translucent view with some of the features called out (below).

The arm system also includes 4 DOF associated with 6 distinct hand grips including chuck grip, power grip, tool grip, fine pinch open, fine pinch closed, and lateral "key" grip. The overall prosthesis and socket interface system is modular and capable of being configured for scapulothoracic (ST), shoulder disarticulation (SD), transhumeral (TH), and transradial (TR) levels of amputation [3].

Multiple control inputs are available for use as part of the arm system, including conventional techniques such as push switches, linear transducers, pressure transducers, and EMG sensors. The control system can also accommodate signals from more recent advancements in targeted reinnervation (TRI) and other central nervous system interfaces in development. A specific goal of the development process was to create a control scheme approach that allowed the prosthetist and the user to work together to choose control methods that are intuitive, effective, and appropriate for the specific situation of each user. Essentially, a toolkit is provided to support the prosthetist and therapist in control scheme development for each user.

With more mechanical degrees of freedom available within the prosthesis, additional control inputs were developed to support greater levels of simultaneous control and support increased usability. Our application of inertial measurement units (IMU) uses MEMS accelerometers and gyroscopes to provide additional DOF of translation and rotation signals and can be implemented at various locations on the body. Because there are typically limited sources of conventional signals for powered prosthesis control (usually 2 EMG, occasionally >2), conventional prosthetic devices are typically controlled in a serial fashion, i.e. from one joint to the next. With the Gen 3 arm possessing the capability of simultaneous powered multi-degree of freedom control and motion, these alternative control schemes allow greater simultaneous control for the user, even given limited EMG sites and without additional surgical intervention as would be required for other advanced or experimental control methods.

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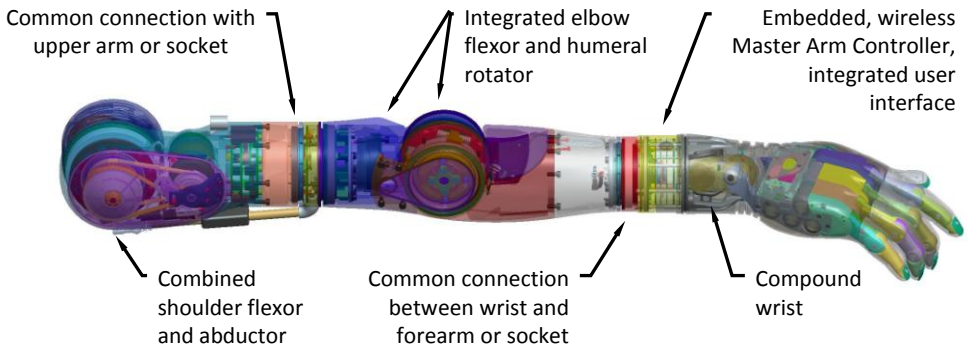

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DESIGN FEATURES

Although numerous elements were important in the design effort, we will discuss two specific elements in more detail. They included 1) development of an efficient/effective means to control a full 10 DOF arm (with powered shoulder), and 2) the functional value of a wrist motion equivalent to ulnar/radial deviation found in the natural limb, a commonly requested articulation parameter by our users; this motion enables more efficient interaction of the prosthetic hand with objects on surfaces that are not at passive elbow height.

ENDPOINT CONTROL

Conventional control of a prosthesis by the user is often joint based, such as explicit command of supination of the wrist or flexion of the elbow. Typically these discrete motions are sequenced together into a series that eventually moves the terminal device of the prosthesis to its intended destination. More recently, certain motions have been bundled together, such as the simultaneous motion of fingers of the hand in an open and close maneuver.

The challenge with higher levels of amputation (ST, SD) is that they require a prosthesis with more degrees of freedom while also having a reduced number of sites to use as signal sources to control the prosthesis.

To address the limitations in control signals available by conventional means, we have instead implemented a method to control the position of the terminal device (hand) in space without primary regard by the user of the particular joint motion and/or sequence that is required to create the motion (Figure 3). The user simply indicates a movement of the endpoint (terminal device) forward/backward, up/down, right/left, or in combination, without needing to be concerned about how the shoulder, elbow or wrist joint needs to be articulated to achieve the ultimate destination.

The wireless IMU based sensors provide an excellent signal source for proportional control of the arm/hand endpoint motion in space. The software interface allows the system to be custom configured for the patient to define thresholds, velocity, and the configuration that is most intuitive to the subject. Thousands of hours of runtime have been logged with this control interface, it has been found to be extremely functional with minimal cognitive burden for the subject

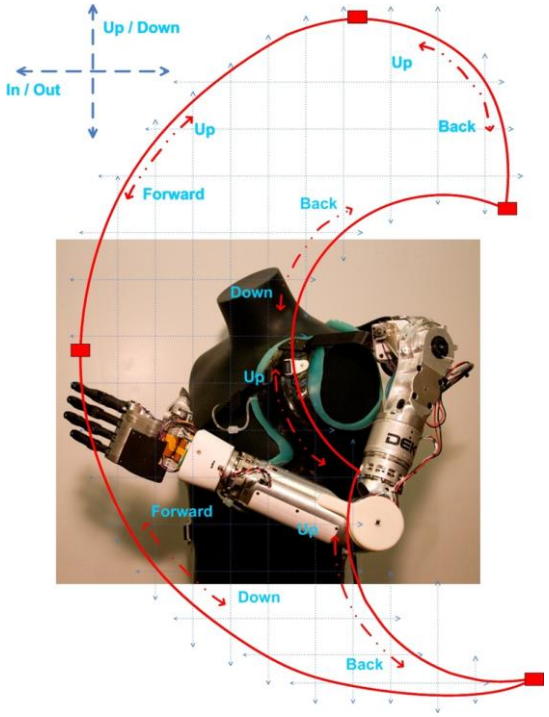

Figure 3. Endpoint control. Gen 2 arm with workspace boundaries.

WRIST ARTICULATION

The need for terminal device motion equivalent to ulnar and radial deviation has been a frequent request from therapists and patients during use of the arm system. This motion enables the subject to interact with and smoothly transfer objects to surfaces that are not at passive elbow elevation. For example, as shown in Figure 4, a bottle securely positioned in power grip requires radial deviation when the subject, in a standing position, plans to place the bottle in a stable perpendicular position on a table surface positioned below passive elbow level.

Figure 4. Examples of the hand in wrist extension-radial deviation position to place a bottle on a surface below the passive elbow position (left) and in a flexed, ulnar deviation position to place a bottle on an overhead shelf (right).

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It is challenging to incorporate three independent DOF in the wrist with the lingering constraints of physical dimension, weight, and moment-arm costs. While the users and experts in the field made it clear that they valued ulnar/radial deviation; they also made it quite clear that they would not take that DOF if it eliminated supination and pronation or flexion and extension.

To assist us with understanding the spatial and temporal activity of the prosthetic arm's individual components, the arm incorporates logging features that allow tracking of positions, loads, and the power consumption of the joints during prosthetic arm activities. This allows the creation of a histogram profile of important parameters related to the various arm components during use. This quantitative data was essential as we progressed through the generations of prosthetic arm development. Based on this data and the observation of the prosthesis by subjects, a compound motion path combining wrist flexion/extension and ulnar-radial deviation was created that fulfilled the majority of wrist position functions required. Figure 5 illustrates the motion path of this hybrid degree of freedom. This allows the subject to access objects on surfaces well above and below the passive elbow position as noted in Figure 4 without requiring the cognitive burden associated with controlling these two DOF independently.

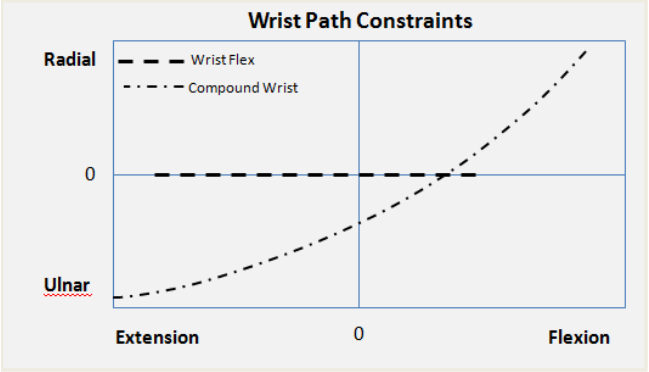

Figure 5. Example of motion curves for a compound (hybrid) wrist motion that incorporates wrist flexion-extension and ulnar-radial deviation

CONCLUSION

The collaboration of engineers, clinicians, and patients has allowed the development of an advanced upper arm prosthesis system that offers significant advances in functionality and capability; this development has required solutions to a variety of difficult design problems regarding arm capabilities, dynamics, and functionality as well as development of innovative control scheme components and improvements in interface design. The prosthesis system is proceeding through the final stages of development with continuing collaboration and feedback from user and prosthetist/therapist communities.

ACKNOWLEDGEMENTS

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