DEVELOPMENT OF THE BENTO ARM: AN IMPROVED ROBOTIC ARM FOR MYOELECTRIC TRAINING AND RESEARCH

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INTRODUCTION

Myoelectric training is a key step in transitioning upper limb amputee patients to a successful myoelectric prosthesis fitting. Although training was found to be important in fittings with children [1], a gap in the literature exists for linking training systems to improved outcomes in adults. In order to close this gap additional studies must be performed to more closely evaluate the effect of different kinds of training on clinical outcomes. Our group hypothesizes that improvements in training pre and post fitting will help improve a patient's confidence in myoelectric control and more closely align their expectations to the current capabilities of myoelectric technology.

A review of myoelectric training devices was previously performed to identify the strengths and weaknesses of existing systems [2]. In general existing commercial systems were found to only allow an amputee to control a single degree of freedom (i.e. hand open/close) using a pair of EMG electrodes placed over antagonistic muscles on the residual limb. Key improvements for future systems included integrating the ability to perform more functional tasks, tracking relevant outcome metrics over time, accommodating both conventional and pattern recognition controllers, and employing a variety of training methods such as signal strength display, video games, virtual reality, and robotic arms.

To address these issues the Myoelectric Training Tool (MTT) was designed to assist in the training and assessment of amputee patients in advance of prosthesis fitting [3]. The MTT was also designed as a research platform for testing novel EMG controllers based on machine learning methods and sensory feedback systems. The original research version of the MTT included a desk mounted off-the-shelf AX-12 smart robotic arm (Crustcrawler, Inc), EMG acquisition system, EMG controller, and graphical user interface. It allowed control of up to two degrees of freedom simultaneously for targeted muscle reinnervation (TMR) patients. More recently a simulated version of the robotic arm and a myoelectric Tetris video game have also been incorporated into the system and the physical robotic arm was upgraded to the slightly stronger AX-18 smart arm. Since 2010 the research version of the MTT has successfully been utilized in subject trials with 15+ able-bodied subjects and 5 upper limb amputee subjects [3-6].

As we pushed the limits of the training tool in research and training applications we discovered certain limitations with the AX-12 and AX-18 smart arms. As seen in Fig. 1 the arm employs two actuators at the elbow and wrist flexion joints to increase the amount of torque available. However, when fully extended and moving at the low speeds typical for myoelectric control the elbow servos would tend to overheat and eventually shut themselves down. This was partly attributed to each actuator in the elbow having its own independent controller which caused synchronization issues, but also the AX-12 and AX-18 actuators were in general underpowered for use in a myoelectric training platform. In practise this meant limiting the payloads used in experiments to less than 50g and the trial times to less than 10 minutes. Some of the other areas we identified for improvement included the shoulder joint, which tended to move jerkily, and the general non-anatomical appearance of the arm, which made it more difficult for subjects to imagine it as a prosthesis. To overcome these issues we decided to build an improved robotic arm, the Bento Arm, designed specifically for our myoelectric training and research applications.

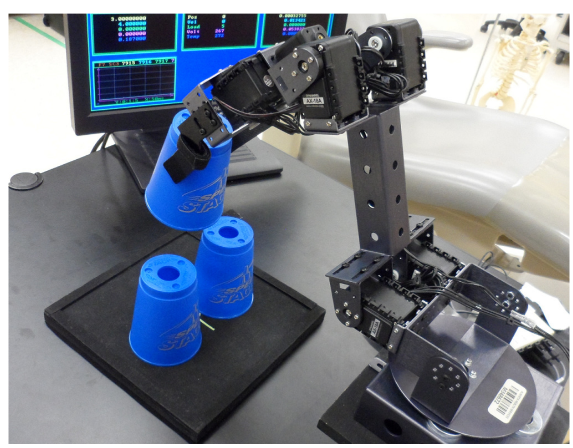

Figure 1 - The AX-18 Smart Arm being used with myoelectric control in a cup stacking task

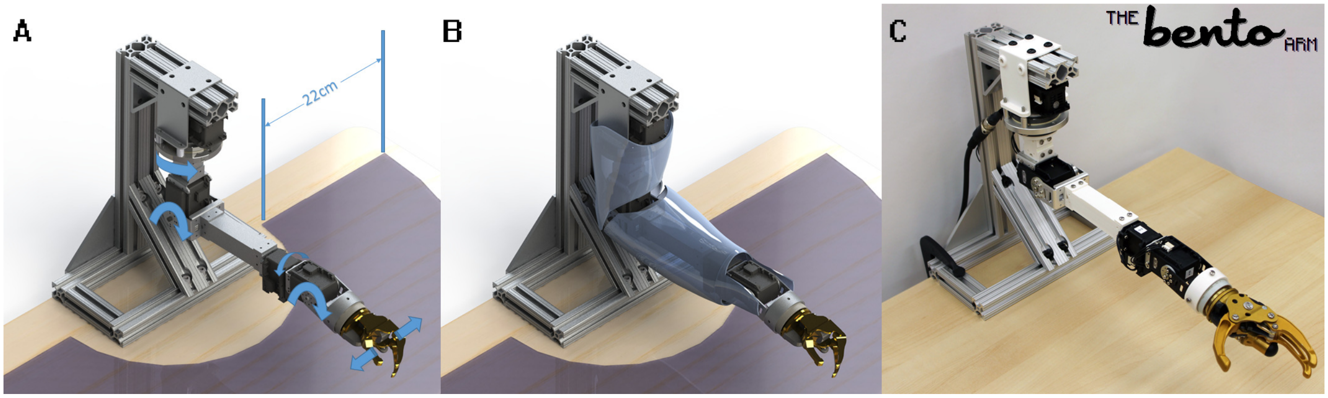

Figure 2 – a) Design specifications showing degrees of freedom and desktop workspace, b) the Bento Arm with removable 3D printed arm shells, and c) the 3D printed prototype of the Bento Arm (shown here without arm shells)

DESIGN SPECIFICATIONS

The preliminary design specifications for the Bento Arm are summarized in Table 1 and Fig. 2a.

Table 1: Design specifications for Improved Robotic Arm

Item	Design Specification
Size	Full scale with anatomically correct proportions
Mass (excluding stand)	≤ 1.5 kg
Payload Capacity	≥ 0.3 kg
Degrees of Freedom	➢ Shoulder rotation ➢ Elbow (flexion/extension) ➢ Wrist rotation ➢ Wrist (flexion/extension) ➢ Hand (open/close)
Actuators	Include position and velocity control and feedback
Workspace	22cm along the surface of the table
Modular wrist connector	Compatible with commercial terminal devices and multi-articulated hands
Prototyping Cost	≤ $5000

To more closely mimic upper limb prostheses the new arm was specified to be 1:1 scale with anatomical proportions to more easily allow the patient to visualize it as an arm. The mass of the arm including terminal device was planned to be less than 1.5 kg to keep it in the same range as myoelectric prostheses with powered elbows. The payload capacity of the arm was specified as 0.3 kg or greater to allow the option to use heavier objects in functional tasks. This payload capacity applied to when the arm was stationary or moving, did not include the weight of the terminal device, and would be sustainable indefinitely without overheating. The available degrees of freedom were specified to match those of commercially available components (elbow flexion, wrist rotation, hand open/close) and provide some degrees of freedom that may be available in the future (shoulder rotation and wrist flexion). To accommodate conventional and novel EMG controllers the actuators required sensors to allow velocity and position control. If possible, the stronger MX series in the Dynamixel line of actuators (Robotis, Inc.) would be used to enable the reuse of interfacing electronics and software already developed for the AX-18 smart arm. A workspace of 22cm was specified to allow compatibility with the modified box and blocks task originally developed for the AX-12 smart arm [3]. A modular wrist connector was desired to allow custom designed and commercial terminal devices to be interchanged, allowing patients to test different prehensor options. The total prototyping cost was specified to be $5000 or less in order to keep the arm inexpensive relative to its capabilities and allow it to be more easily duplicated in additional setups.

For the detailed design of the arm the specifications were further subdivided into mechanical, electrical, and software categories. Whenever feasible off-the-shelf or open source components were selected to reduce the design time and allow the prototype to be more easily duplicated.

MECHANICAL DESIGN

Initially, a basic kinematic model of the robotic arm was developed in SolidWorks 2014 to determine the combination of link length and joint range of motion required to meet the 22cm work space and anatomical proportion requirements. These lengths and joint ranges were then used with known component weights in iterative calculations to estimate the torques required to provide the desired payload capacity. From previous testing of the MX series actuators it was determined that they can support up to approximately half of the rated stall torques when moving an object at speeds typical of myoelectric prostheses. In order to accommodate the higher torques at the proximal elbow and shoulder joints the heavier and more powerful MX-106T and MX-64T actuators were selected respectively. An iglide PRT slewing ring bearing (Igus, Inc.) was used at the shoulder to isolate the MX-64T actuator from the weight of the arm and allow for smooth rotation. The lighter and smaller MX-28T actuators were chosen for the wrist and hand joints in order to decrease the distal bulk and mass of the arm. Through testing it was determined that a bearing would not be required at the wrist rotation joint.

The SolidWorks assembly model was updated with the selected components and the links, brackets, and adapters to interface between them. The associated aluminium brackets manufactured especially for the MX series were selected for the joints. The remaining custom designed square tubing links, brackets, and adapters were specified to be 5052 aluminium when bending was required and 6061 aluminium otherwise. Notches were added to the square tubing links to allow for easy routing of actuator and sensor cables and an 8020 beam (80/20 Inc.) stand was designed to enable the arm to be rigidly mounted or clamped to a table or desk and to allow for mounting of electronic enclosures.

To improve the visual appearance of the arm and allow it to be more easily identified as a prosthesis, arm shells were designed as seen in Fig 2b. A 3D scanner was used to scan the arm of one of the authors and the resulting CAD file was converted to a solid body and shelled out in SolidWorks. The upper arm and forearm shells were each split into an upper and lower section and secured to the square tubing to allow for easy assembly and removal. If desired, the realism of the shells could be further improved by painting in skin tones or covering with fabric, gel, or silicone materials.

ELECTRICAL DESIGN

The MX series actuators are designed to be daisy chained together on a bus and controlled by digital packets via a serial communication protocol. The protocol allows a control computer to send position and velocity commands to each actuator on the bus as well as poll for feedback on position, velocity, temperature, and load. A 12VDC, 150W power supply (Iccnexergy, Inc.) and a power switch (CW Industries) were specified to power the bus and allow it to be turned on and off independent of the control computer. An USB2dynamixel controller (Robotis, Inc.) was selected to interface between the actuators and a control computer via USB. A custom designed controller developed for the AX-12 arm is also available that allows the MX bus to interface with a RS-232 port. An electronics enclosure mounted in the stand houses all of the controllers and the power switch. Cables are routed through the square tubing whenever possible and kept neat with 3D printed guides or zip ties.

To allow the wrist to be compatible with commercial terminal devices a quick disconnect wrist (Ottobock, Inc.) was acquired. A 7.5VDC, 30W power supply (Triad Magnetics, Inc.) was specified to provide power and a custom control interface was designed to allow a commercial prehensor to be connected to two analog output channels on a data acquisition card. The interface was tested with a SensorHand Speed (Ottobock, Inc.) as shown in Fig. 2c, but should be compatible with any myoelectric terminal device that can run off a 7.0-8.0 V battery pack and that expects an analog voltage from EMG electrodes between 0 and 5V.

SOFTWARE DESIGN

One of the advantages with choosing the Dynamixel line of actuators is that Robotis has openly published their serial communication protocol. Thus, in addition to their own software interface which support Microsoft Windows and Linux in a variety of languages there is a strong community built around the actuators that have developed additional interfaces for platforms such as Mac OS X, Robotic Operating System (ROS), and Arduino Boards. In theory any of these could be used to control the arm. However, to allow the arm to be used in myoelectric training and research, we developed the following modular software interfaces that interface the arm with a Bagnoli-8 EMG acquisition system (Delsys, Inc), National Instruments data acquisition cards, conventional or machine learning based EMG controllers, and graphical user interfaces (GUI).

MATLAB's xPC Target

A software interface utilizing MATLAB's xPC Target real-time operating system has previously been developed for the MTT [3]. With xPC Target a backend computer runs in real-time and a frontend computer allows signals to be displayed and parameters to be controlled. The main features of the backend controller include a signal processing module for EMG, a modified RS-232 driver to communicate with the Dynamixel bus, and a conventional EMG controller. The frontend GUI was built in Microsoft Visual Studio 2008 and graphically displays the EMG signal strength and allows the operator to change and save all the threshold, gain, mapping, and robotic arm settings.

Robotic Operating System

Recently, we developed a control interface for the Bento Arm based on the Robot Operating System (ROS), an open source software architecture for robotics that includes a wealth of existing packages and tools. ROS is built on a robust messaging architecture with packages for data logging and playback, visualization, dynamic simulation, graphical interfaces, kinematics and motion planning, as well as support for numerous commercial sensors and actuators. While ROS is not a real-time operating system, it has the advantage that it may be possible to run both controller and GUI on a single laptop or embedded computer, or conversely in a distributed manner.

The graphical interface is built on rqt, a ROS GUI builder. It communicates with the actuators via the USB2dynamixel controller and includes features to pause, turn torque on or off and return the arm to a home position. A proportional EMG controller was also designed with adjustable parameters such as channel threshold, max, and gain. Feedback on EMG signal strength as well as the currently selected joint for each channel pair is also displayed in the GUI.

PROTOTYPE & SOCKET INTEGRATION

To accelerate development custom 1" square tubing links, brackets, and adapters were 3D printed in white PLA on a Replicator 2 desktop 3D printer (Makerbot, Inc.) as seen in Fig 2c. An infill percentage of 50% was used in order to optimize the effective strength of the 3D printed parts while saving as much weight as possible [7]. After assembling the arm, functional testing with the ROS interface was able to proceed rapidly. During assembly several improvements in adapter and bracket design were identified and will be incorporated into the final aluminium parts. Initial testing suggests that arm should be able to achieve all of the design specifications listed in Table 1.

During development, it became apparent that the Bento Arm could potentially be mounted to a socket and used as an experimental prosthesis in a research setting. To test the feasibility of this idea an acrylic adapter was mounted to a clear thermoplastic socket (Fig 3). In addition to the research benefits of having a wearable arm, since the PLA version of the arm only weighs 500g from the elbow down (excluding terminal device), it could potentially allow earlier functional training for patients who cannot yet tolerate the full weight of a commerical myoelectric prosthesis.

FUTURE WORK & CONCLUSIONS

While the 3D printed PLA parts were sufficient for pre-prototyping and functional testing we are not confident they will endure long-term testing with the higher payloads and potential impacts with the environment. Consequently, we will proceed with machining the final components out of aluminium. Other improvements to the hardware setup will include developing an array of custom grippers for situations when commercial terminal devices are not available and designing an integrated embedded controller and battery power system to allow subjects to use the arm untethered.

Moving forward with the software systems, we will build a simulation in Gazebo (a ROS integrated robotics simulator) for the Bento Arm as well as integrate it with Rviz (a ROS visualization tool). Additionally, we will create an interface to allow motion planning via MoveIt! (a ROS motion planning tool).

Figure 3 – The Bento Arm integrated with a test socket

In conclusion, the Bento Arm is an affordable, fully sensorized, experimental robotic arm designed specifically for myoelectric training and research. The Bento Arm provides an early training option to potentially help improve clinical outcomes for myoelectric prosthesis fittings. Future research will focus on using the arm to investigate clinical training protocols, novel machine learning controllers, and sensory feedback systems.

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