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TITLE: Myoelectrically Controlled Power-Assist Upper Extremity Exoskeleton

PRINCIPAL INVESTIGATOR: Kenton Kaufman, PhD, PE

CONTRACTING ORGANIZATION: Mayo Clinic, Rochester, MN

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Kenton Kaufman, PhD, PE

E-Mail: kaufman.kenton@mayo.edu

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200 First Street SW
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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Upper extremity peripheral nerve injuries accounted for 6% of all recorded battlefield injuries during Operation Iraqi Freedom. Upper extremity peripheral nerve injuries are the silent, unrecognized injuries that result in loss of function and sensation in specific patterns depending on the nerves that are injured. In the most severe form, a traumatic brachial plexus avulsion injury, all the nerves to the upper extremity are severed, resulting in an upper extremity lacking motor function and sensation from shoulder to hand. This injury is akin to a functional amputation; the extremity is present, but completely nonfunctional. Restoration of elbow flexion is the primary goal following brachial plexus injury since it is a critical motion for daily living. Multiple surgical options exist to achieve this goal. There is a delay of 6 – 12 months after surgery before muscle reinnervation occurs and muscle strength takes 2 years to mature. During this period a powered exoskeleton would be beneficial for assistance with functional activities. The objective of this program is to design, develop, and validate a powered exoskeleton system to assist elbow flexion in patients with traumatic peripheral nerve injuries who have inadequate motor function. Over the initial year of this project, we have performed the mechanical and electrical designs of the powered exoskeleton. The component elements of the initial design have been integrated into an initial prototype. A myoelectric control algorithm has also been created.

15. SUBJECT TERMS
Peripheral nerve injury, brachial plexus, exoskeleton, orthotic, bionics

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1. INTRODUCTION

Upper extremity peripheral nerve injuries accounted for 6% of all recorded battlefield injuries during Operation Iraqi Freedom. In contrast, amputations accounted for 2.7% of injuries. Upper extremity peripheral nerve injuries are the silent, unrecognized injuries that result in loss of function and sensation in specific patterns depending on the nerves that are injured. In the most severe form, a traumatic brachial plexus avulsion injury, all the nerves to the upper extremity are severed, resulting in an upper extremity lacking motor function and sensation from shoulder to hand. This injury is akin to a functional amputation; the extremity is present, but completely nonfunctional. Restoration of elbow flexion is the primary goal following brachial plexus injury since it is a critical motion for daily living. Multiple surgical options exist to achieve this goal. There is a delay of 6 – 12 months after surgery before muscle reinnervation occurs and muscle strength takes 2 years to mature. During this period a powered exoskeleton would be beneficial for assistance with functional activities. The ***objective*** of this program is to design, develop, and validate a powered exoskeleton system to assist elbow flexion in patients with traumatic peripheral nerve injuries who have inadequate motor function. This project addresses “optimization of Warfighter performance following limb trauma or loss”.

2. **KEYWORDS:** Peripheral nerve injury, brachial plexus, exoskeleton, orthotic, bionics

3. ACCOMPLISHMENTS

- **What were the major goals of the project?**
  This project has three specific aims.
  (1) Perform an analysis of the engineering requirements and design the powered exoskeleton
  (2) Develop an EMG algorithm that measures user intent
  (3) Perform efficacy testing of clinical patients using the system in a laboratory setting

- **What was accomplished under these goals?**
  The overall vision for the device comprises a powered exoskeleton to be donned on the affected side (Figure 1). The exoskeleton will be neurologically controlled by the user and respond directly to their intent to move via an EMG signal associated with initiation of muscle movement, which will be processed using a microprocessor-controlled algorithm. The battery, motor, and electronics is in a small backpack that the user will wear. The primary goal in this first year of the study were to perform the engineering analysis to meet the design goals and build an alpha prototype. This goal has been accomplished as follows:

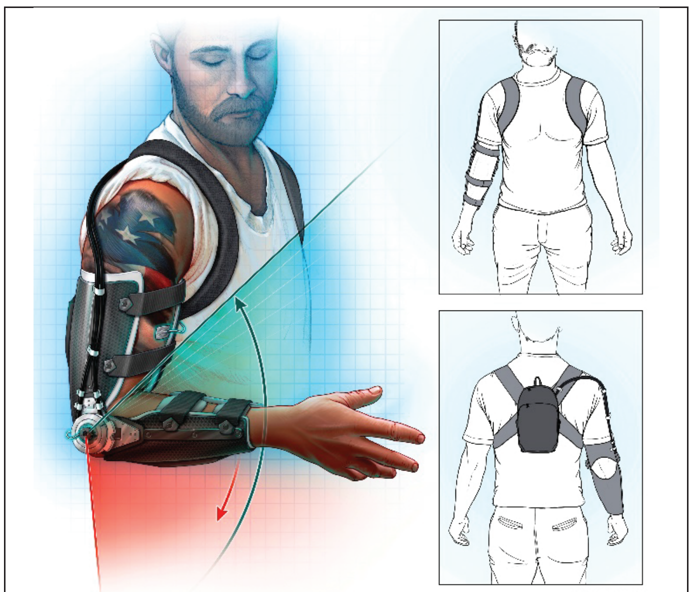

Figure 1. Design concept for the myoelectrically-controlled power-assist upper-extremity exoskeleton (powered exoskeleton).

Aim 1. Electromechanical design
We designed a system that uses a motor, belt drive, ball screw and break-away mechanism to allow for volitional control of additional elbow flexion and passively lock the system to resist elbow extension (Figure 2 & 3). The motor control system is worn on the back and a Bowden cable is used to transmit the pulling force to the elbow

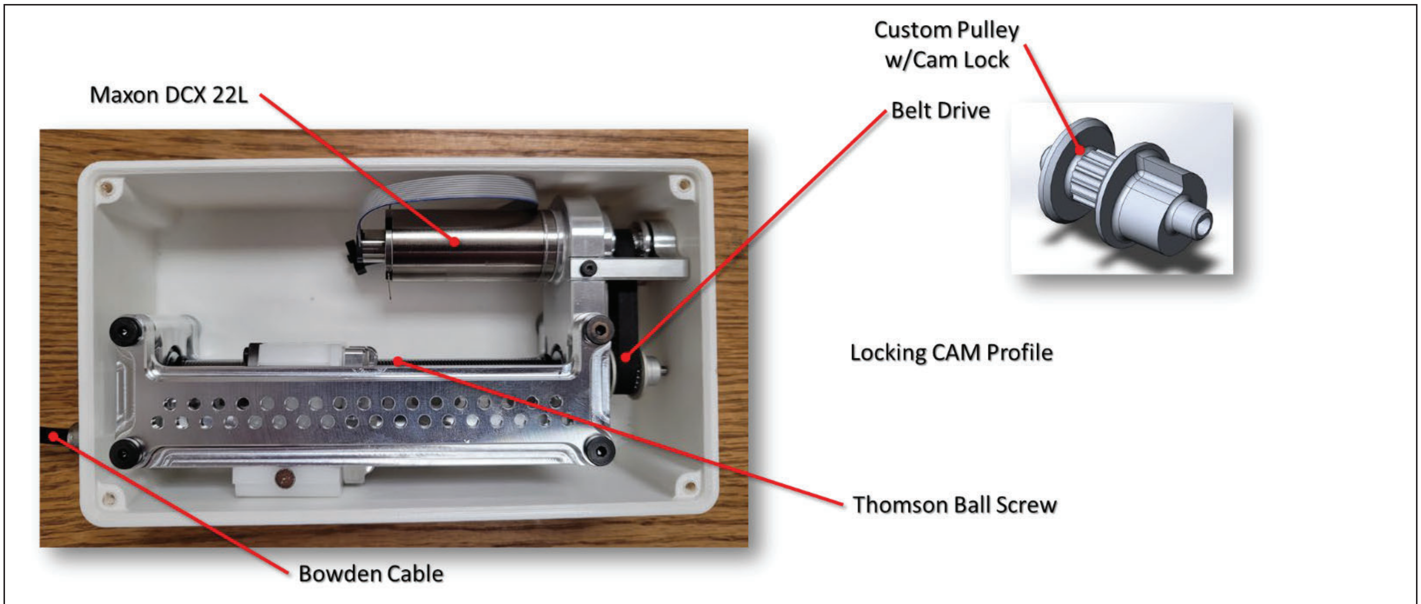

Figure 2. Ball screw drive and back drive locking mechanism.
A Thomson 1mm pitch, 8mm diameter ball screw was selected as the primary drive mechanism. The ball screw is linked to the DC electric motor via a 1.43:1 belt drive system. To prevent back drive, a custom pulley/cam/locking solenoid system was created to passively allow elbow flexion and passively resist elbow extension. A solenoid is activated to allow the system to drive in the elbow extension direction.

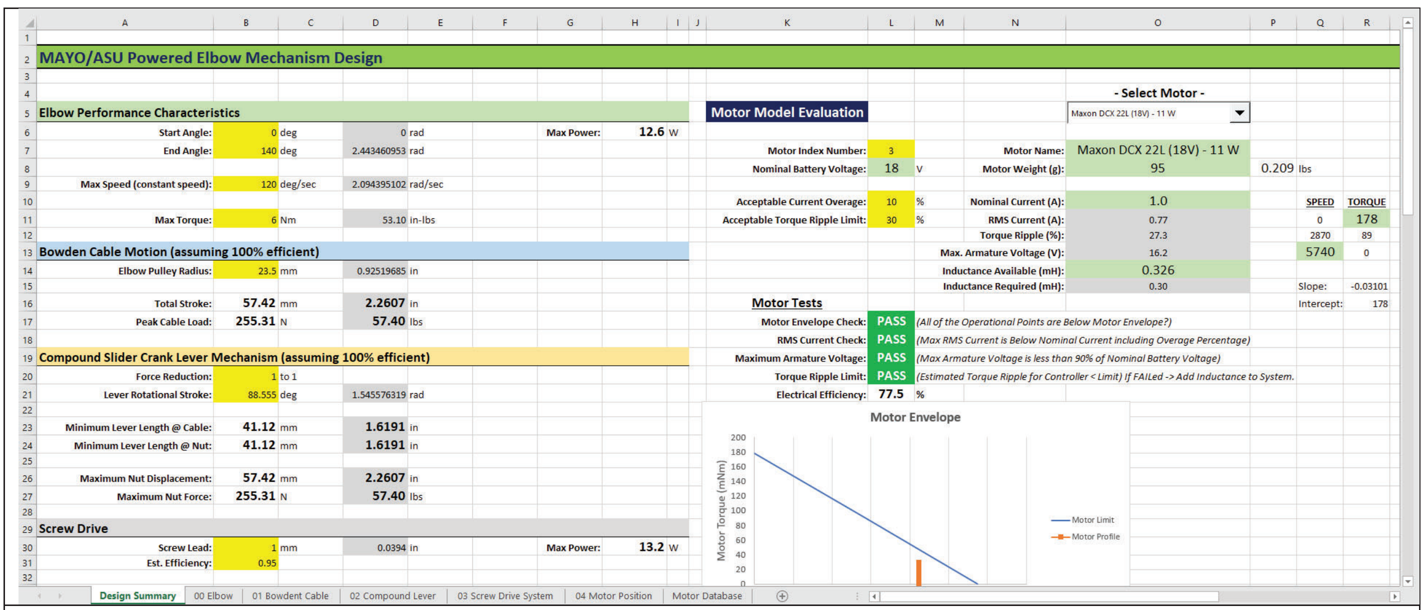

Figure 3. Motor Selection
A Maxon DCX 22L (18V) – 11W motor was selected for the prototype. Motor performance (i.e. envelope), RMS current, Armature Voltage and Torque ripple were all considered in the design. Estimated combined mechanical and electrical system efficiency was calculated to be 77.5% overall.

The elbow joint mechanism was designed to provide flexion assistance for either the left or right arm (Figure 4). The only modification required is the insertion location of the Bowden cable sleeve and a 180-degree reversal of the connection to the cable barrel end. A sensor aligned with the mechanism joint, will sense flexion angles.

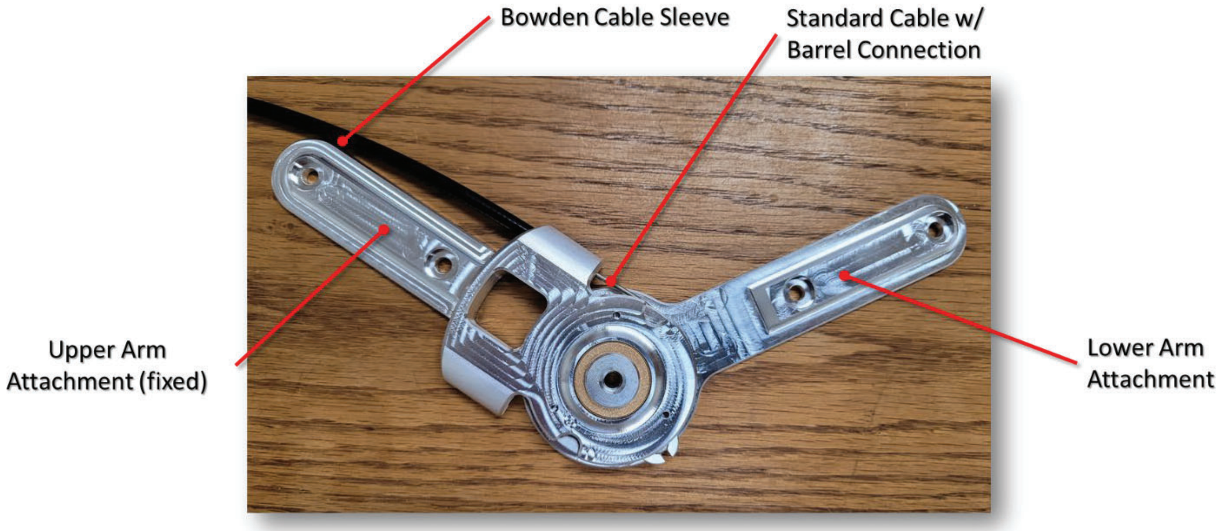

Figure 4: Elbow joint mechanism

<u>Safety Considerations</u>: Numerous features were incorporated into the engineering design to assure safe operation by the user. These included the following:
Release mechanism: The participant needs to be able to manually release the drive mechanism in case the mechanical system fails and is locked at a fixed position.
Motor:

- Loss of electrical power
  - When the participant is moving the arm, the elbow joint will lock in place and avoid sudden extension with loss of electrical power.
  - If the motor fails to activate while the participant is in a static position, they will be able to flex their arm.
- If the motor continues to operate without stopping, there will be a fail-safe stop to prevent the elbow from continuing to flex, which result in injury to the user.

Other design considerations:

1. Mechanical stops are added to the actuator system to physically stop elbow movement. The stops were moved from the elbow joint to eliminate pinch points.
2. If the motor heats, it will be shut it based on temperature
3. Design specification: total weight 5 lbs, target weight of 2.5 lbs. 1lb actuator, 1lb battery, 0.4 lbs at the elbow
4. Cannot be charged when worn
5. Full day of operation 8-16 hours, 12 hour average
6. Around 500 elbow extensions per day
7. Battery mounted on the outside of the backpack

Future testing planned:

1. EMI: Testing will be performed when the prototype has been shown to work properly
2. Drop test
3. There will be a quick disconnect for the battery

Aim 2. Control Algorithm
The user will don the orthosis on their affected side and use their muscle activity to activate an

electrical motor to provide the user power-assist, allowing them to achieve their desired movement. The orthosis will lift the affected forearm using the electrical motor and descend using the weight of the arm. The electromyographic (EMG) signals will be collected and processed by a microprocessor-controlled algorithm and respond directly to the user's motion intention. In the past year, the algorithm control scheme has been designed and development is underway.

- **What opportunities for training and professional development has the project provided?**
  The project has been an avenue for the professional development of Dr. Sandesh Bhat, a post-doctoral research fellow. Through his involvement in this project, he has gained precious insight into the control algorithms utilized in a powered exoskeleton. He has worked on refining his skills to control an electromechanical system in real-time. He has also gained an understanding of clinical problems that need engineering solutions.

- **How were the results disseminated to communities of interest?**
  Since this was the first year of this project, no results have been disseminated at this time.

- **What do you plan to do during the next reporting period to accomplish the goals?**
  - Complete building of alpha prototype
  - Test the prototype operation
  - Identify and redesign components that require modifications
  - Build beta prototype
  - Begin submitting publications

4. IMPACT

- **What was the impact of the development of the principal discipline(s) of the project?**
  Nothing to report.

- **What was the impact on other disciplines?**
  Nothing to report.

- **What was the impact on technology transfer?**
  Nothing to report.

- **What was the impact on society beyond science and technology?**
  Nothing to report.

5. CHANGES/PROBLEMS

- **Changes in approach and reasons for change**
  No changes to report.

- **Actual or anticipated problems or delays and actions or plans to resolve them**
  None

- **Changes that had a significant impact on expenditures**
  Nothing to report.

- **Significant changes in use or care of human subjects**
  None.

6. PRODUCTS

- **Publications, conference papers, and presentations**
  Nothing to report.

- **Website(s) or other Internet site(s)**
  Nothing to report.

- **Technologies or techniques**
  Nothing to report.

- **Inventions, patent applications, and /or licenses**
  Nothing to report.

- **Other products**
  Nothing to report.

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

- **What individuals have worked on the project?**

Name:	Kenton Kaufman, PhD, PE
Project Role:	Principal Investigator, Mayo Clinic
Nearest person month worked:	2
Contribution to Project:	Dr. Kaufman has held regular meetings with the study staff. He has led the design meetings. He has prepared materials for the Mayo IRB and HRPO. He has served as the liaison with the DOD and has provided the required quarterly and annual reports.
Funding Support:	

Name:	Sandesh Bhat, PhD
Project Role:	Post-doctoral Fellow, Mayo Clinic
Nearest person month worked:	1
Contribution to Project:	Dr. Bhat has served as an engineer for the project. He is working to develop the real-time control algorithm. He attended regular meetings with the Co-Investigators.
Funding Support:	

Name:	Emily Miller, MS
Project Role:	Research Engineer, Mayo Clinic
Nearest person month worked:	2
Contribution to Project:	Ms. Miller has worked to develop the control algorithm. She attended regular meetings with the Co-Investigators.
Funding Support:	

Name:	Paul Kane, BS
Project Role:	Research Engineer, Mayo Clinic
Nearest person month worked:	1
Contribution to Project:	Mr. Kane has worked on the electrical and mechanical designs

	of the prototype. He attended regular meetings with the Co-Investigators.
Funding Support:	

Name:	Eric Noonan, BS
Project Role:	Research Engineer, Mayo Clinic
Nearest person month worked:	1
Contribution to Project:	Mr. Noonan has worked on the prototype smart phone app to provide user control of the exoskeleton. He attended regular meetings with the Co-Investigators.
Funding Support:	

Name:	Thomas Sugar, PhD
Project Role:	Site Principal Investigator, Arizona State University
Nearest person month worked:	1
Contribution to Project:	Dr. Sugar is the ASU site principal investigator for the project. He attended all study meetings and coordinates the work being accomplished at ASU. The focus this year has been on …
Funding Support:	ASU sub award

Name:	Kevin Hollander, PhD
Project Role:	Lead Mechanical Engineer
Nearest person month worked:	2
Contribution to Project:	Lead mechanical designer. Dr. Hollander has twenty years of experience in designing orthoses, prostheses, and exoskeletons. He attends all study meetings
Funding Support:	ASU sub award

Name:	Claudio Vignola
Project Role:	Graduate Research Assistant
Nearest person month worked:	2
Contribution to Project:	Integrating the mechanical design with the microprocessor and electronics. He attends all study meetings
Funding Support:	ASU sub award

Name:	Alex Boehler
Project Role:	Lead Electronics Specialist
Nearest person month worked:	1
Contribution to Project:	Mr. Alexander Boehler is an electronics expert in prosthetics and exoskeletons. He is developing commercial grade microprocessor units to control the motor and integrate the EMG signal
Funding Support:	ASU sub award

- **Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?**
  No.

- **What other organizations were involved as partners?**
  Nothing to report.

8. SPECIAL REPORTING REQUIREMENTS

- **Collaborative Awards**

- **Quad Chart**

9. APPENDICES