WrexoFlexor: A Flexible Wrist Exoskeleton for Muscle Strength and Control Rehabilitation

Rafael Valbuena, Jacob Rinda, Megan Dierking, Christopher Moss, Alec Arvia

Department of Mechanical Engineering and Bioengineering, Valparaiso University, Valparaiso, IN, USA

Problem Statement and Background

Over 795,000 cases of stroke are reported in the United States each year. Stroke often accelerates or introduces physical disabilities, and a loss of dexterity and weakness in the wrist is common. Physical therapy is often necessary to regain strength and motor control. [1] However, physical therapy can be prohibitively expensive because of extensive one-on-one time patients require with therapists. Increasing the efficiency of therapy sessions by automating the therapist's task of providing resistance to a patient's wrist and providing therapists with robust, quantitative measurements of patient progress has the potential to reduce the cost to the patient.

The following device objective was developed:

The Flexible Wrist Exoskeleton (FWE) is a device intended to provide customizable load impedance to the wearer during wrist flexion/extension and radial/ulnar deviation, in addition to collecting data on user wrist movement during virtually integrated rehabilitation exercises.

The following design requirements were then developed:

1. Be wearable on an average size adult wrist
2. Be flexible across the range of motion required for physical therapy exercises
3. Be safe to wearer during operation
4. Provide adjustable loading on a wearer's wrist up to a minimum of 8 lbs. during wrist flexion/extension and radial/ulnar deviation
5. Record data on wrist motion and device settings for later review
6. Include integrated User Interface (UI) for intuitive operation and limited user programming

Methods and Solutions Considered

Providing force on the wrist during movement requires either constant damping to wrist motion or a continuous force applied to the wrist. While damping would effectively facilitate concentric contraction (shortening a muscle while resisting a force), it would not be capable of providing resistance for exercises requiring eccentric (lengthening a muscle while resisting a force) or isometric (static resistance to a force) contractions. A combination of all three contraction modes provides optimal results in muscle strength and conditioning programs, and allows patients to practice dexterity and motor control under varying and realistic loading conditions. Thus, a variably resistive elastic element was chosen as the preferred mechanism to provide force on the wrist.

A system consisting of a cranked wheel and motor that would crank and release the elastic element was briefly considered, but the high complexity and design challenges required to implement the system were considered too significant. Linear actuators were chosen as a simpler and immediately purchasable mechanism of varying the length of the elastic bands.

Affixing the resistive elements and actuators to the patient could be achieved by affixing the patient to a static device or affixing a moveable device to the patient. To maximize patient comfort, a non-static solution was selected. A full-forearm wrist brace was selected as the base of the device because of its comfort and adjustability to accommodate patients of varying arm sizes.

Wrist motion measurement requires either continuous measurement of the wrist angle or an optical or inertial motion capture system. Motion capture and traditional digital goniometers are prohibitively expensive and complex. A flexible resistor that changes resistance while bending was chosen for simplicity and low cost. Sensors were calibrated with a goniometer to provide accurate wrist angle measurement.

An effective user interface could consist of visual feedback on the device, connection to a graphical user interface on an external digital device, audio feedback from the device, or any combination of the three. An audio UI with limited physical switching on the device was selected as the optimal solution due to its operational simplicity (no external devices or additional controls needed) and accessibility for individuals with a visual disability.

A microcontroller processor is required for operating the actuators with respect to wrist position, data collection, and providing the user with an interactive user interface. The Arduino Uno, Arduino MKRZero, MSP430, Raspberry Pi were considered. The MKRZero was selected because it provided sufficient storage and analog inputs in the smallest achievable form factor and power usage.

Description of Final Approach and Design:

A. Frame

The Frame is a three-part system composed of a modified wrist stability brace, a glove and an elastic sleeve (Figure 3).

- The sleeve is the first component worn by the user and it serves three main purposes: 1) protect the user from any moving parts, 2) it includes pockets that house the flex sensors and 3) electrically insulate them from the user’s skin.
- The brace was modified with a cut along the wrist joint in order to allow the user to freely move in the two desired DOF. It provides attachment points for the linear actuator mounts.
- The glove was also modified by attaching four snap fits to the top, bottom and sides which serve as anchor points for the exercise bands during the exercises.

B. Impedance System

The impedance system is composed of two P16-P Actuonix linear actuators that can be mounted either on the superior/inferior or medial/lateral sides of the user’s forearm. Each actuator includes one elastic band attached to its end, with the other end of the band attached to the glove being worn on the user’s hand. Once activated, the linear actuators pull the elastic bands back, proving a variable tension force on the user’s wrist. The elastic bands exhibit a quasi-linear force-displacement behavior governed by Hooke’s law. Our team verified the force-displacement curves of each elastic band using an uniaxial load frame(MTS, QTest 150) (Figure 1).

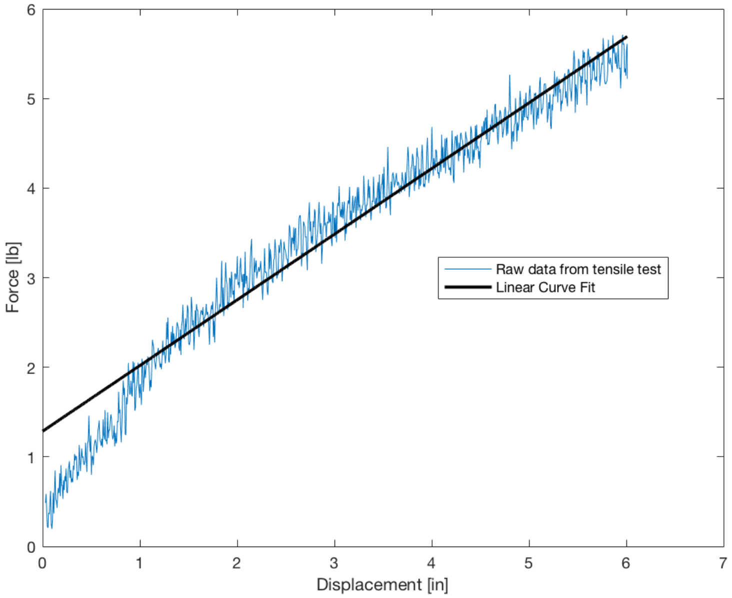

Figure 1. Representative sample of force-displacement data for the exercise bands used in the FWE. Notice there is a "settling" behavior in the first inch of displacement where force-displacement curve shows a non-linear behavior. However, between one and six inches, the load-displacement curve exhibited a linear behavior, indicating that constant loading would be imparted during device operation.

C. Microcontroller

An Arduino MKRZERO microcontroller controls the linear actuators using a PWM signal. The duty cycle from the PWM signal is directly proportional to the length of the linear actuators, making it simple to modify the length of the elastic bands attached to the actuators. The microcontroller also receives inputs from the flex sensors and determines wrist angles using a previously generated calibration curve. We generated the calibration of the flex sensors using a manual goniometer as a standard for wrist flexion/extension angles. This data is also stored in an SD card for later review and progress tracking. A plot of sample data generated by the system is provided in Figure 2.

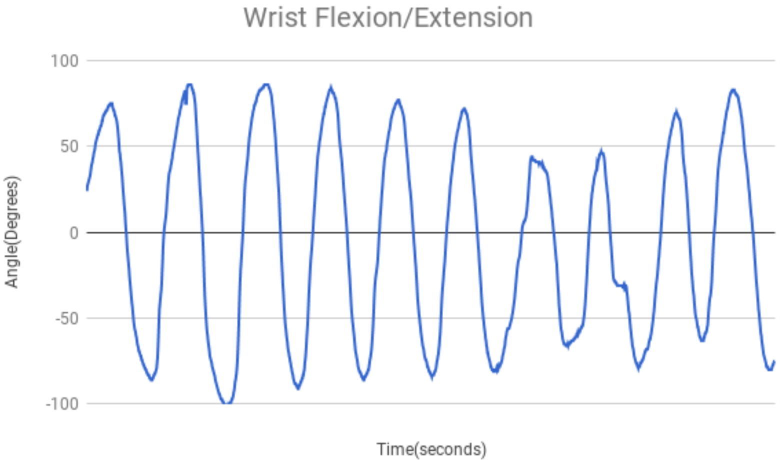

Figure 2. This is sample wrist flexion/extension angle data, recorded during a test session. The user performed ten flexion/extension repetitions while wearing the WrexoFlexor.

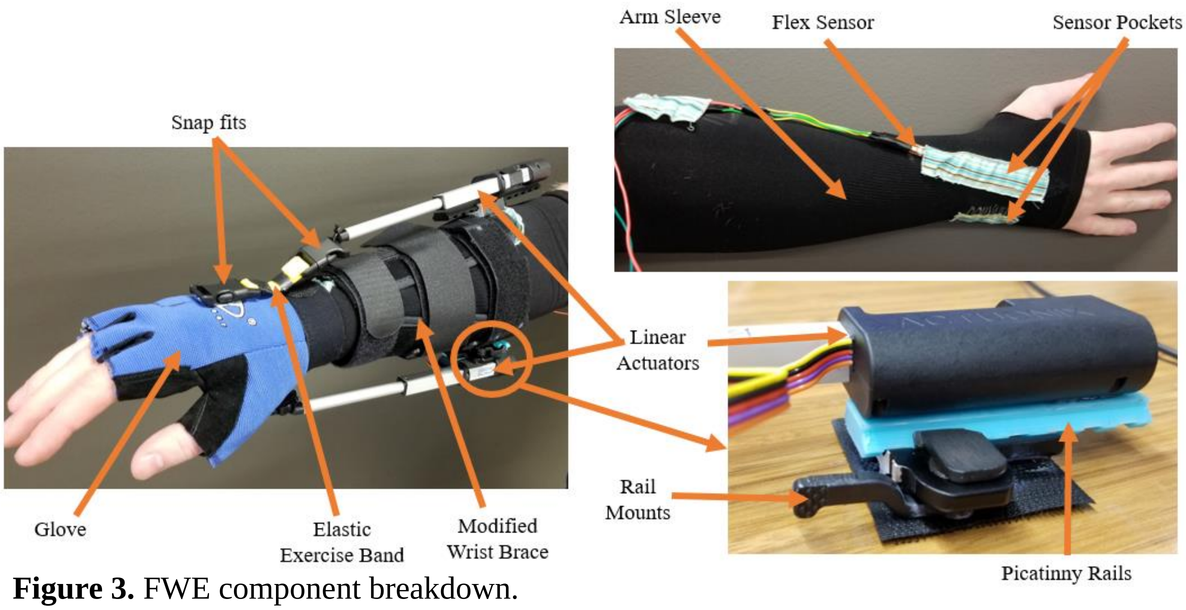

Figure 3. FWE component breakdown.

D. User Interface

A speaker is the main component of the FEW's user interface. It uses pre-programmed audio cues to guide the user through the rehabilitation experience. The interface includes two distinct modes of operation (Figure 4.). The first mode is:

Program Mode which allows the user to select the desired level of impedance. The impedance level can range from 1 to 10, with 1 being the least amount of force and 10 being the hardest load resistance. The user can easily change levels with a simple hand gesture while a recorded voice provided information about the current level. The second mode is:

Impede Mode which indicates the linear actuators to retract increasing the resistance provided on the user's wrist to the level selected during program mode. During this mode the controller also records the angle data and creates a file in the SD card.

The user can manually change between modes with an included hardware switch.

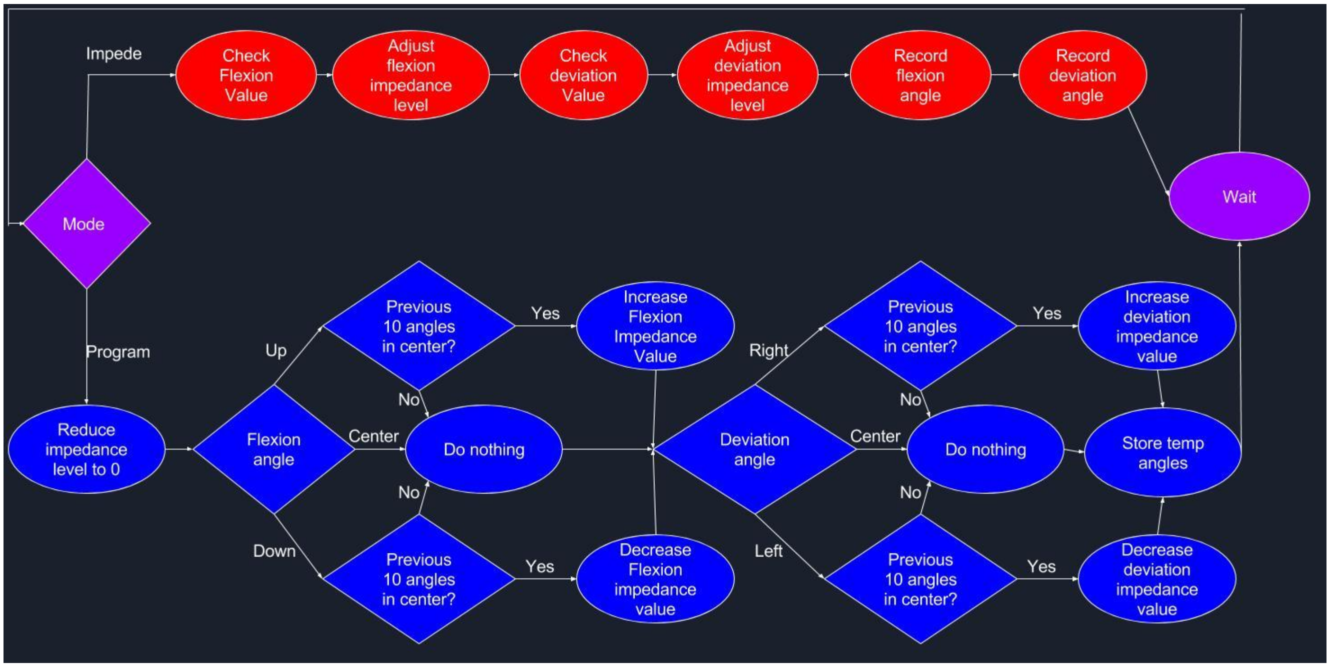

Figure 4. Flow-chart describing the FEW's user interface logic

Outcome

Preliminary testing has demonstrated that the FWE is comfortable to the wearer during extended periods of operation (>30 minutes) and successfully provides continuous near constant force on the wrist over a full range of motion. Figure 2 shows wrist angle measurements collected during preliminary testing. Reduction of calibration error is the primary area of improvement that must be addressed. The gesture interface and audio UI were intuitive and easy to operate, and changing force levels through the gesture interface was easy. Elastic elements were easily and quickly substituted to provide more or less force on the wrist.

Cost

The estimated total cost of the proposed system is $422.93 USD. This cost only includes materials and components used. A breakdown of the cost of the device is provided in Table 1.

Table 1. Cost breakdown of the FEW system

Component	**Quantity**	**Price/unit**	**Source**
4.5” Flex sensors	2	$12.95	Sparkfun
2.2” Flex sensors	2	$6.16	Sparkfun
Mini Power Switch	1	$1.50	Sparkfun
Arduino MKR Zero	1	$21.90	Arduino
Adafruit speaker	1	$1.95	Adafruit
Adafruit AMP	1	$5.95	Adafruit
Linear Actuator and Control Board	2	$110	Actuonix
microSD card	1	$9.89	SanDisk via Amazon
Athletic Resistance Bands set	1	$8.99	Sable via Amazon
Wrist and Forearm Splint	1	$13.29	Medline via Staples
Throw Lever Dovetail Rail Mounts	4	$12.99	JJ Airsoft
Airsoft 12” Rails	1	$14.84	AIM Sports via Amazon
5/8” Snapfit 10 pack	2	$5.90	Paracord Planet via Amazon
Athletic Sleeve	1	$9.99	Shinymod via Amazon
Superweld Adhesive	1	$5.18	Walmart
RW Performance Glove	1	$7.47	Menards
Total Cost		**$422.93**	

Included in the table above are all the components we purchased to manufacture one prototype. The total cost for us to produce this prototype was $422.93. It should be noted that the provided cost does not include components that were readily available to us such as the (Hewlett-Packard, E3610 DC Power Supply, 3D printed parts, and a laser engraved PCB. Everything listed in Table 1 went into the creation of a single prototype. As such, the manufacturing cost would decrease due to using the excess resistance bands, snap-fits, glove, and athletic sleeve. Buying other products in bulk such as the rails and flex sensors would also decrease the cost.

Significance

In standard wrist rehabilitation, a physical therapist (PT) works one-on-one with a patient during most of their exercises. The PT provides resistance to the patient’s wrist and assesses the patient’s progress with a mixture of quantitative and qualitative measurements. Effective therapy can be complex and require many lengthy sessions, and the cost of the PT's time is shouldered by the patient. In addition, a lack of robust quantitative measurement can result in busy therapists progressing a patient through a rehabilitation program more quickly or slowly than what is optimal.

The FWE addresses both issues with a wearable device that produces customizable resistance curves for a patient's wrist in two dimensions while recording the angle of the patient's wrist and the force applied on the wrist at all times. The device can produce resistance for concentric, eccentric, and isometric exercises, and is easily adjustable and customizable through a modular design and an audio-feedback programming system. Patients can perform preprogrammed, predetermined exercise routines, freeing therapists from one-on-one interactions with that single patient. The therapist can instead focus more time on quantitative assessments of patient progress, future exercise progressions, or other patients entirely. More efficient therapy sessions and better programming of exercise sessions could result in shorter or less sessions required for a patient, reducing the time and cost of recovery.

Future Work

Additional progress includes finalizing calibration of the radial/ulnar deviation flex sensor for angle measurements and developing displacement curves for the actuators when operating in deviation. Tensile testing of elastic elements needs to be conducted to develop more accurate force-displacement curves.

Acknowledgements

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References

[1] Center for Disease Control, 2017. *Stroke Facts*. Retrieved from https://www.cdc.gov/stroke/facts.htm