Characterization of Sensors employed in an automated Knee Brace for Leg Muscle Rehabilitation

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Introduction

In a current project at San Jose State University, an automated orthotic knee joint is being developed that will assist rehabilitation of partially paralyzed patients. This device uses electromyography sensors to gather impulse signals and uses pneumatic actuators in the form of fluidic muscles. A microcontroller is used to interpret the signals from the sensors and uses a feedback control loop to provide augmented strength and mobility to the wearer. Various types of sensors are used to monitor the brace operation that include rotary encoders, force, and electromyography sensors. For an accurate functioning of the knee brace, it is important to characterize these sensors before these are embedded in the system. The work presented here will describe the methods that were used to characterize and calibrate force sensors and rotary encoders selected for this project. The Keyes KY-040 rotary encoder used here is a rotary input device that provides an indication of how much the knob has been rotated along with its direction of rotation. To calibrate this sensor, an Arduino was used in conjunction with an experimental setup where the rotation of the encoder was simultaneously recorded with a protractor attached to the encoder. A 3D printer was used to develop the encoder holder that was embedded inside the knee. To measure the applied force as the knee brace is moved in an upward direction, a 0.5-inch FSR402 (thin film pressure sensor) was selected. Before implementing the sensor inside the system, it was calibrated and for this purpose a calibration stand was designed and constructed. The work presented here will describe in detail the methodologies adopted for calibration of two sensors and will present the calibration curves for both sensors. The discussion will also include preliminary experimental results for the knee-brace movement (angle) mounted on a mannequin leg as a function of fluidic pressure.

Objectives

1. To select sensors required to characterize an automated knee brace developed at San Jose State University
2. Investigate techniques and procedures to calibrate these sensors that include rotary encoder and force sensor.
3. Develop experimental rigs to conduct calibration tasks.
4. Construct calibration charts for the sensors under investigation.
5. Test these sensors by mounting them on the mannequin leg and obtain experimental data

Project Background/Literature Survey

- Stroke is one of the leading cause of disability in the United States. Approximately 795,000 suffer from stroke every year
- There are many patients who have lost control of their leg muscles due to having a stroke. Patients need to rehabilitate their leg muscles to be able to walk independently. For this, they would need physical therapy sessions to help recover their leg muscles, which can be expensive and time consuming.
- Several kinds of assistance is available that includes:
  - Prophylactic helps prevent knee injuries for athletes
  - Rehabilitation braces help recovery after surgery
  - Functional braces provide knee support after surgery
  - Unloader braces applies force to pressure points of the leg to help alleviate pain.
- Commercially available systems include:

The RoboKnee [Ref 1]

- An exoskeleton for enhancing both strength and endurance during walking
- It has the ability to apply forces when and where they are appropriate
- The RoboKnee allows for the users to not only climb stairs but also perform deep knee bends while under a heavy load.
- The RoboKnee can determine the user's intent through the knee joint angle and the ground reaction forces.

The C-Brace [Ref 2]

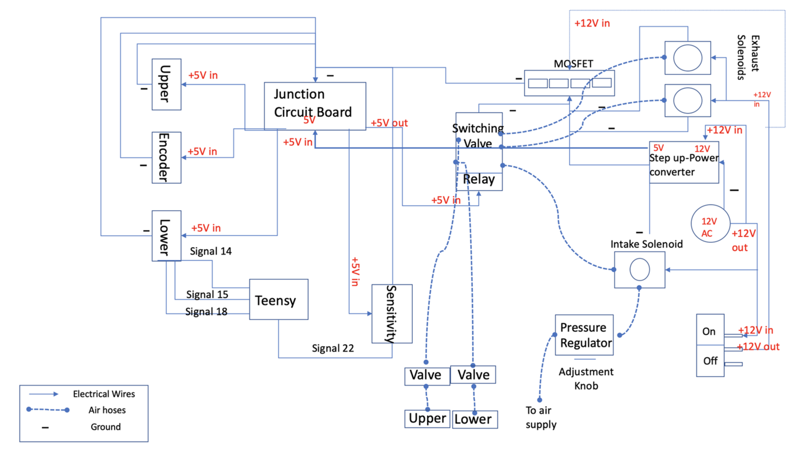
- Consists of individually fabricated thigh, calf, and foot components
- Sensors measure the flexion of the knee joint and its angular acceleration
- These sensors allow for the knee brace to detect the current walking pace of the user
- Flexion and extension of the knee joint is then varied accordingly

Honda Walking Assist Device [Ref 3]

- Comprised of 3 components: hip frame, leg motors, and thigh frame
- The movement of the pelvis, acting as an inverted pendulum, uses the legs as pivot points to achieve smooth and efficient bipedal walking
- The device also detects movements of the hip joint and helps guide the initial kicking movement of the lower leg when walking
- It will then verify the left and right symmetry of the leg movements to achieve proper operation.

"Above mentioned knee assisted braces are complicated in design and are expensive. The automated knee assisted brace at SJSU is simple in design and in its operation. It uses fluidic muscles to mimic the movements of the actual quadriceps and hamstring muscles. It controls movements via electromyography sensors attached to the user's leg."

Knee Brace Developed at SJSU



Electronic Circuit with all components.
Power is driven by a +12V source and is converted into a +5V source by using different power converters.

Knee Brace

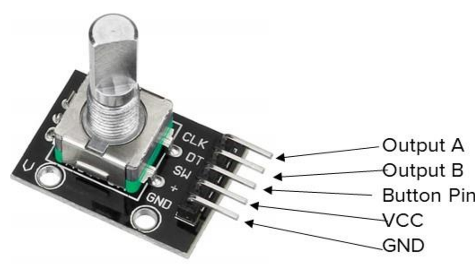
Range of motion	~70-180 degrees
Unit Weight	<10lbs
Cost	~$6000
Device Training	1-2 training sessions
Force supplemented	25% of body weight
Operation Time	~30mins-1hr/session
Controller response time	0.1 secs (faster than human reaction)

Design Criteria

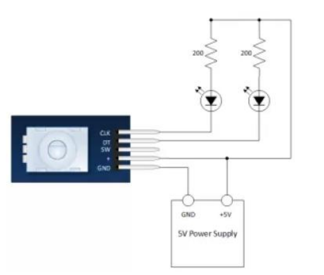
Working Principle of the Knee Brace

This device uses electromyography sensors to gather impulse signals and uses pneumatic actuators in the form of fluidic muscles. A microcontroller is used to interpret the signals from the sensors and uses a feedback control loop to provide augmented strength and mobility to the wearer.

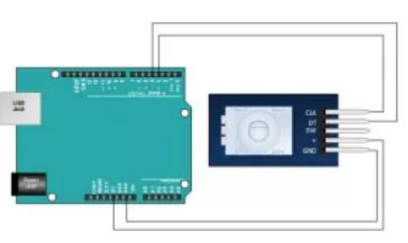
Sensors Implied: Rotary Encoder



KY-040 Rotary Encoder

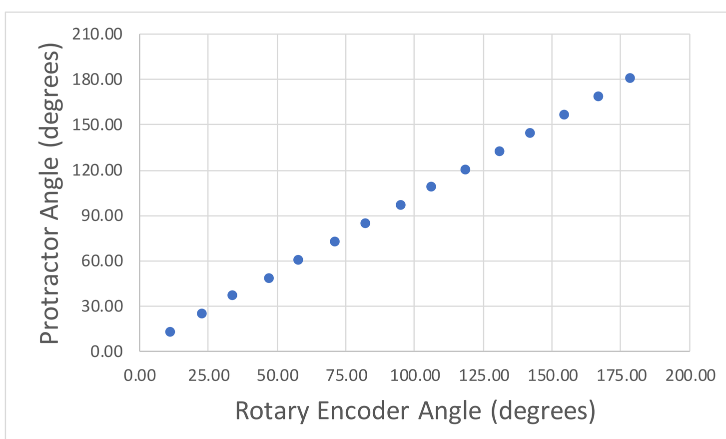


Rotary Encoder's Evaluation Circuit



Arduino attached to the encoder

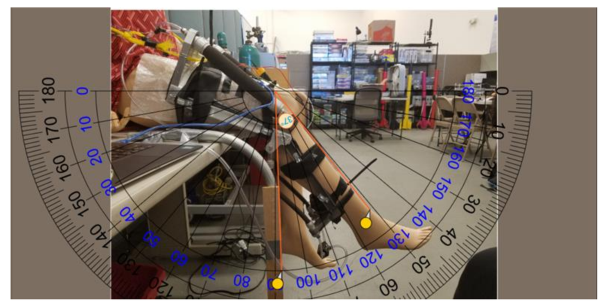
- A rotary encoder is a device used to determine angular position
- Within the sensor there is a rotating shaft that will generate an electrical signal that can be received by a microcontroller
- Keyes KY-040 Rotary Encoder was used in this study. An evaluation circuit shown above was used to evaluate the performance of the sensor. A mini microprocessor Arduino was used to control and extract information on rotation angles.
- The Arduino was also used to calibrate the encoder by attaching a protractor along with a rotatable pointer that was directly attached to the encoder.



The calibration curve was constructed and is shown as a straight line indicating a linear trend.

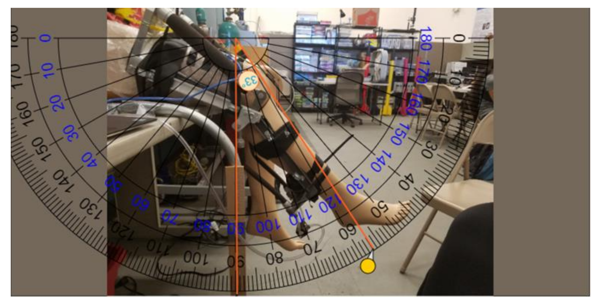
Rotary Encoder's Attachment to the Brace: Experimental Results

3D Printed housing to mount the rotary encoder onto the mannequin leg.



Mannequin leg rotation

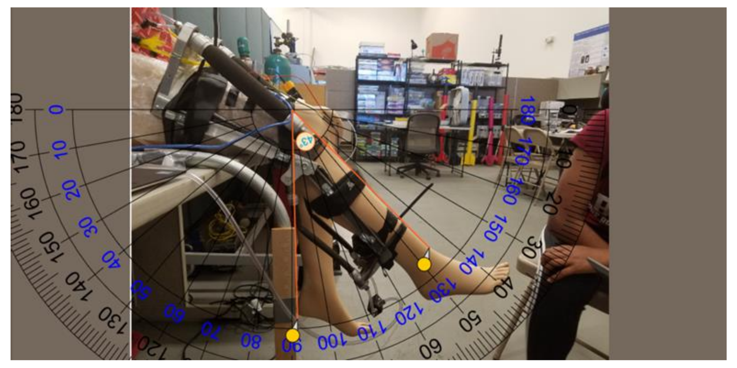
Applied Pressure 55 psi



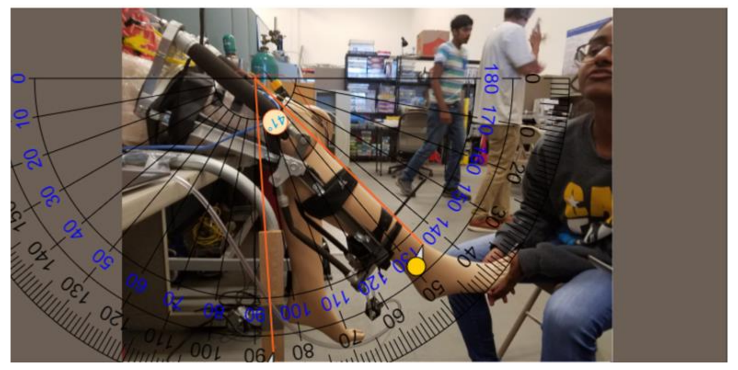
Mannequin leg rotation

Applied Pressure 60 psi

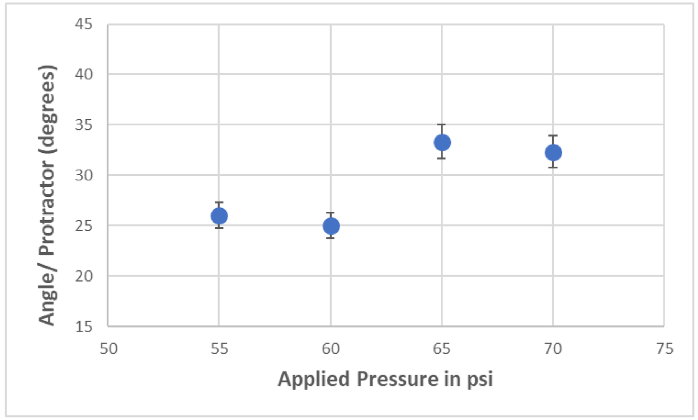
- The knee brace was mounted on the mannequin leg and was attached to the electronic control circuit. Several Arduino circuits were employed to measure the rotary encoder angles. Rotation angles were also verified by using a protractor.
- Mannequin leg rotation in degrees measured using a protractor as a function of applied pressure (55, 60, 65 and 70 psia).



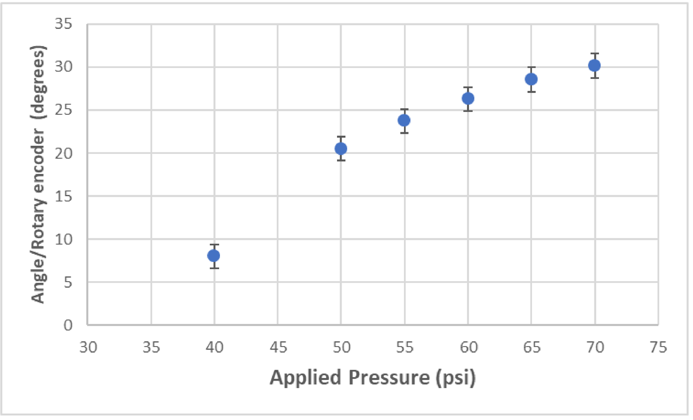
Mannequin leg rotation: Applied Pressure 65 psi



Mannequin leg rotation: Applied Pressure 70 psi



Leg rotation angle measured by a protractor as a function of applied pressure



Leg rotation angle measured by a rotary encoder as a function of applied pressure

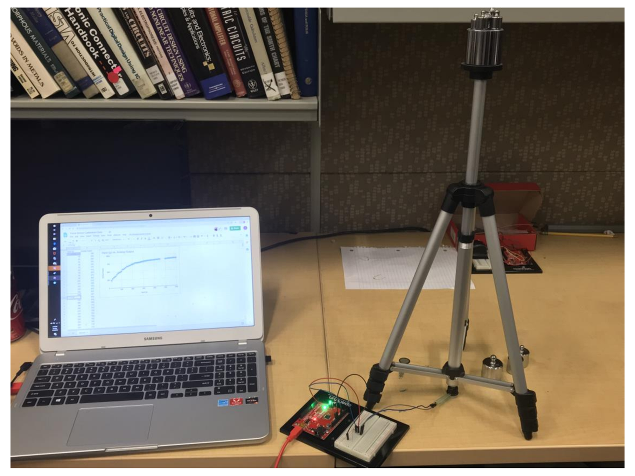
Force Sensor calibration

- FSR 402 (13 mm Circle × 56 mm) sensor was used for this experiment
- An electrical circuit provided by the manufacturer was used to get the sensor output.

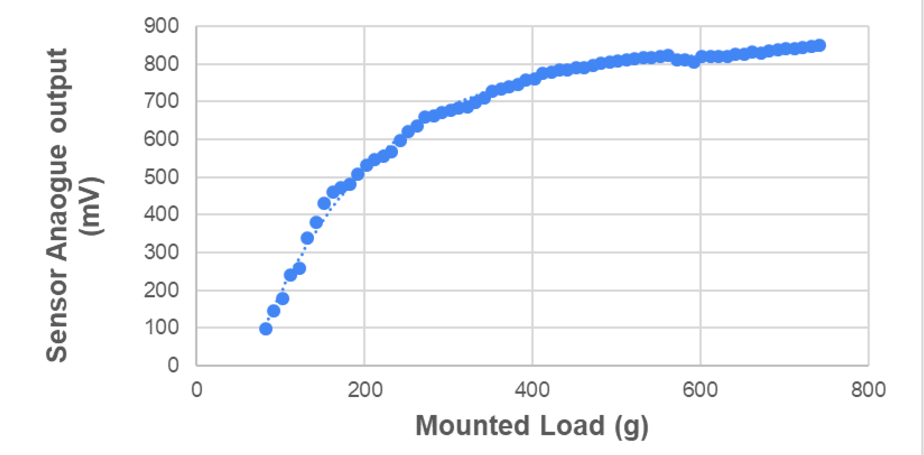
Device Characteristics

Actuation Force*	~ 0.2N
Force Sensitivity Range*	~ 0.2N - 20N
Force Resolution	Continuous (analog)
Force Repeatability Single Part	+/- 2%
Force Repeatability Part to Part	+/- 6% (Single Batch)
Non-Actuated Resistance	> 10 Mohmas
Hysteresis	+10% Average (RF + -RF-)/RF+
Device Rise Time	< 3 Microseconds
Long Time Drift - 1kg load, 35 days	< 5% 1og10(time)
Operating Temperature Performance - Cold: -40˚C after 1 hour - Hot: +85˚C after 1 hour - Hot Humid: +85˚C 95RH after 1 hour	-5% average resistance change -15% average resistance change +10% average resistance change
Storage Temperature Performance - Cold: -25˚C after 120 hours - Hot: +85˚C after 120 hours - Hot Humid: +85˚C 95Rh after 240 hours	-10% average resistance change -5% average resistance change +30% average resistance change
Tap Durability - Tested to 10 Million actuations, 1kg, 4Hz	-10% average resistance change
Standing Load Durability - 2.5kg for 24 hours	-5% average resistance change
EMI	Generates no EMI
ESD	Not ESD Sensitive
UL	All materials UL grade 94 V-1 or better
RoHS	Compliant

- In order to calibrate the force sensor, an electronic circuit proposed by the manufacturer was used that provided output voltage of the senor as a function of applied load in grams.
- These kind of force sensors can give up to ~23% errors in measurements as noted in [ref 4]. The calibration technique and sensor's application procedure was adopted from [ref 4].
- A custom stand was designed to ensure that during the calibration, the applied load remains perpendicular to the entire sensor's surface.
- To ensure that the applied load is uniformly distributed over the sensor's surface, a thin rigid disc was inserted between the stand and the force sensor. The diameter of the disc was equal to that of the sensor.



Force sensor calibration apparatus



Force sensor's calibration curve

- In the current study, the force sensor is being mounted over the mannequin leg to obtain the applied force on the leg as a function of the applied pressure.

- Special thanks to Sisira Sakhamuri, Visiting Scholars from Pusan National University (The Republic of South Korea): Sohyun Ryu, ChangGeun Kwon and Pranav Bellannagari for their input to this project.

Conclusion and Future Directions

1. Assistive knee-brace developed at SJSU was mounted on a mannequin leg to evaluate its performance. An air compressor was used to operate the system.
2. Several electronic systems incorporating Arduinos were mounted on the leg to control and monitor the rotary motion of the leg as the applied air pressure was varied.
3. A special bracket was fabricated to mount the rotary encoder on the leg.
4. Calibration for two sensors including the rotary encoder and the force sensor were performed and calibration curve for both sensors were obtained.
5. Mannequin leg rotation angle as a function of applied air pressure was obtained.
6. Rotary encoder's angle rotation measurements were compared with the readings obtained from the protractor. Two measurements were found close enough.
7. Current work is focusing on mounting the force sensors on the mannequin leg to obtain applied force on the leg as a function of air pressure.

Citations

[ref 1] Nagel, V., Chu, S., Forney, J., Kosinski, L., and Viswanathan, V., 2017, "Design and Control of an Assistive Bionic Joint for Leg Muscle Rehabilitation," *in the proceedings of ASME 2017 International Mechanical Engineering Congress and Exposition*

[Ref 2] Pratt, J.E., Krupp, B.T., Morse, C.J., Collins, S.H. (06 July 2004). *The Roboknee: an exoskeleton for enhancing strength and endurance during walking* . doi:10.1109/ROBOT.2004.1307425 (2017). *C-Brace.* Retrieved from: https://www.ottobockus.com/orthotics/solution-overview/c-brace-orthotronic-mobility/c-brace.html

[Ref 3] *Honda Walking Assist Device.* Retrieved from: https://global.honda/products/power/walkingassist.html

[Ref 4] Jirapat Likitlersuang, Matthew J. Leineweber, Jan Andrysek, Evaluating and improving the performance of thin film force sensors within body and device interfaces, Medical Engineering and Physics 48 (2017) 206–211