Using Force Sensors to Effectively Control a Below-Elbow Intelligent Prosthetic Device

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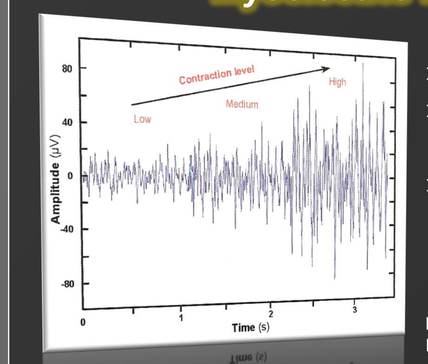
introduction

- US troops in Iraq required limb amputations at twice the rate of past wars (The Boston Globe, 2004)
- 795 amputations for soldiers in Iraq and Afghanistan since December 2001 (The Seattle Times, 2007)

Figure 1: Wounded Soldier (thememoryhole.org, 2004)

review of literature

Myoelectric Prosthetic Control



- »Current applied state-of-the-art
- »Residual muscle contractions control hand movements
- »Uses myoelectric signals (MES) created by muscle contractions to control motor rotation (Muzumdar 2004)

Figure 2: Variation of Myoelectric Signal with Contraction Level (D.F. Lovely, 2004)

Problems with Myoelectric Control

- »Inaccurately predicts muscle contraction one out of every 20 times (L. J. Hargrove et al., 2007)
- »Surgical implantation necessary for accurate pattern recognition (Muzumdar, 2004)
- »Signal processing necessary to remove electrical noise (L. P. J. Kenney et al., 1999)
- »Each electrode can cost $2000 (P. Kyberd, 2007)

Force Sensors – A Better Solution?

- »Piezoelectric devices (change in applied pressure results in change in output voltage)
- »Can measure muscle contraction
- »Never before used in multi-sensor, pattern recognition setup with the purpose of controlling a prosthesis (L.J. Kenney et al., 1999)

Advantages of Force Sensors

- »Less Expensive ($20 each) (www.parallax.com)
- »No Surgery Needed
- »Potential to Eliminate or Reduce Need for Signal Processing

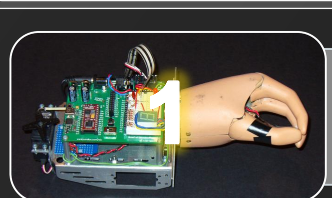
hypothesis

Muscle Contraction

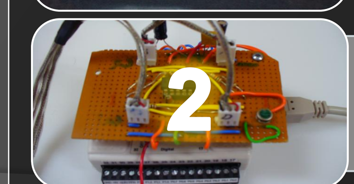
Existing Method	Novel Method
Indirect Measurement	Direct Measurement
Implanted Myoelectrodes	Forearm Force Sensor
95% Accuracy	Accurate?

Below-Elbow Prosthetic Device

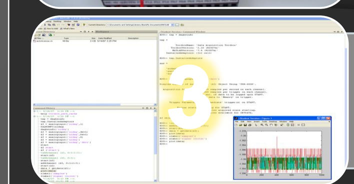
objectives



1. Build proof-of-concept hand



2. Develop computer interface and acquire raw data



3. Write and implement input analysis program

results and discussion

1. Prosthetic Prototype

Figure 12 (a-d): (From left) Servo actuator and vibration amplification circuit board; hand with vibration sensor; LED # Force Readout (scale of 0-6); Vibration Warning LED (Blum, 2007)

- ✓ Hand opens and closes upon force input
- ✓ Force Approximation
- ✓ Hand can grip objects
- ✓ Slip circuit successfully arrests slip

2. Computer Interfaced Force Sensor Circuit

The muscle being contracted should show the highest voltage to indicate proper differentiation (Channel color matches title color)

Muscles Relaxed

(a) Inactive Calibration Data for Myoelectrodes (b) Inactive Calibration Data for Force Sensors

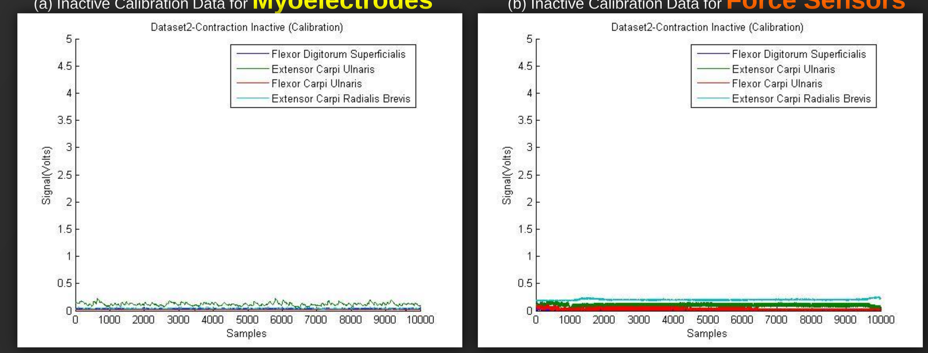


Figure 13 (a & b): Inactive Myoelectrode and Force Sensor Calibration Data (Blum, 2007)

Finger Flexion *(Flexor Digitorum Superficialis)*

(a) Active Calibration Data for Myoelectrodes (b) Active Calibration Data for Force Sensors

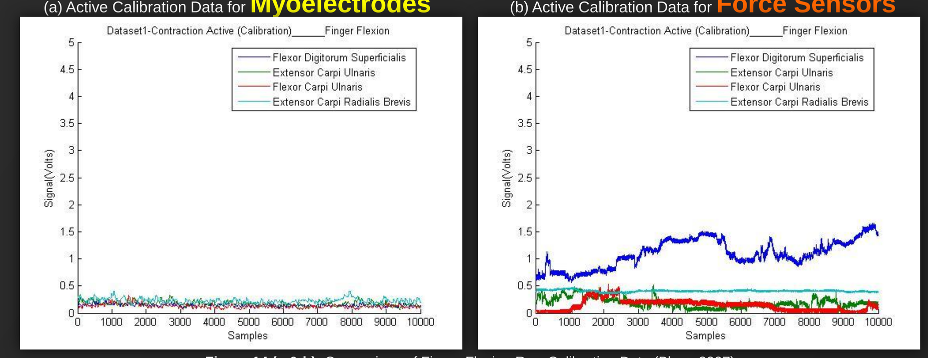


Figure 14 (a & b): Comparison of Finger Flexion Raw Calibration Data (Blum, 2007)

Finger Extension *(Extensor Carpi Ulnaris)*

(a) Active Calibration Data for Myoelectrodes (b) Active Calibration Data for Force Sensors

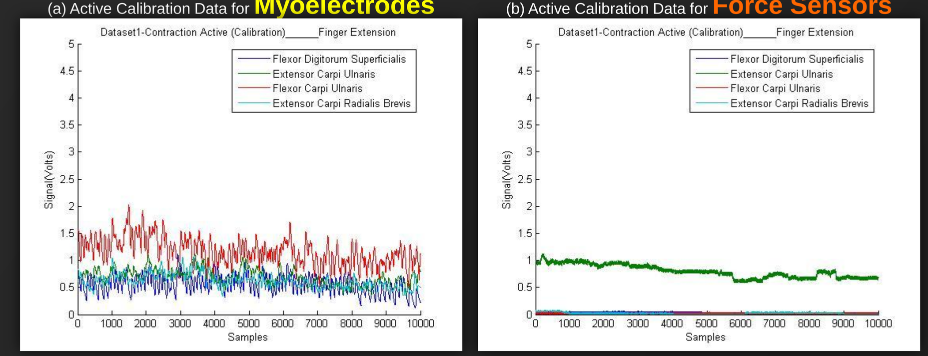


Figure 15 (a & b): Comparison of Finger Extension Raw Calibration Data (Blum, 2007)

Wrist Flexion *(Flexor Carpi Ulnaris)*

(a) Active Calibration Data for Myoelectrodes (b) Active Calibration Data for Force Sensors

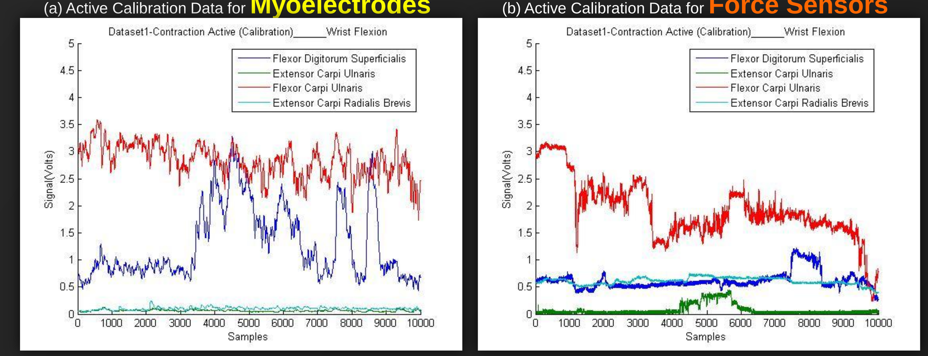


Figure 16 (a & b): Comparison of Wrist Flexion Raw Calibration Data (Blum, 2007)

Wrist Extension *(Extensor Carpi Radialis Brevis)*

(a) Active Calibration Data for Myoelectrodes (b) Active Calibration Data for Force Sensors

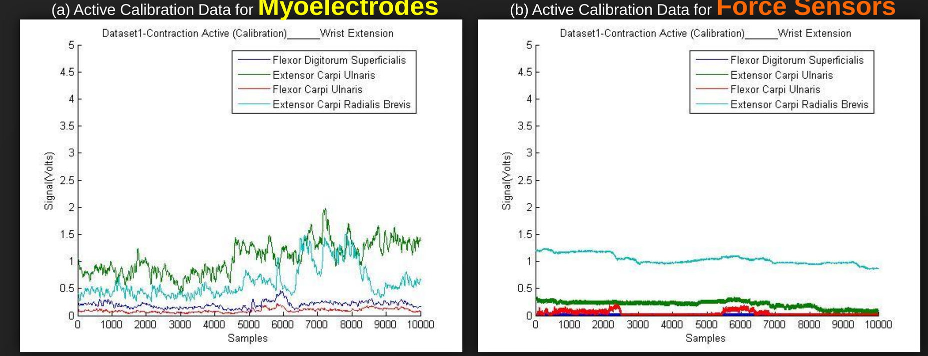


Figure 17 (a & b): Comparison of Wrist Extension Raw Calibration Data (Blum, 2007)

3. Computer Analysis Program

Since finger extension is the action being tested, only the finger extension SVEN graph should surpass zero (red line) at any point

Finger Extension *(Extensor Carpi Ulnaris)*

(a) Action Data for Myoelectrodes (b) Action Data for Force Sensors

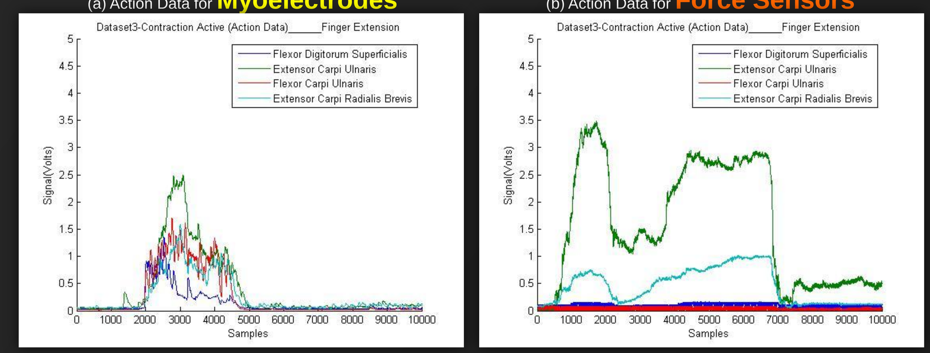


Figure 18 (a & b): Myoelectric and Force Sensor Finger Extension Action Data for SVEN Function (Blum, 2007)

Finger Flexion ≠ Finger Extension *(Should not exceed zero)*

(a) SVEN Function for Myoelectrodes (b) SVEN Function for Force Sensors

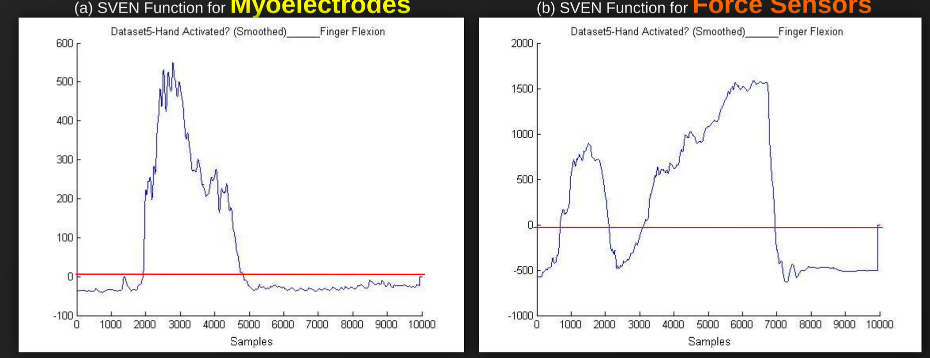


Figure 19 (a & b): Myoelectric and Force Sensor Finger Extension Smoothed SVEN Function (Blum, 2007)

Finger Extension = Finger Extension *(Should exceed zero)*

(a) SVEN Function for Myoelectrodes (b) SVEN Function for Force Sensors

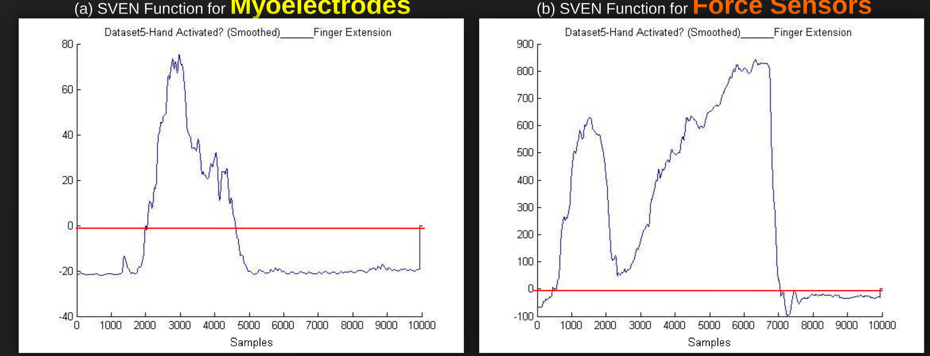


Figure 20 (a & b): Myoelectric and Force Sensor Finger Extension Smoothed SVEN Function (Blum, 2007)

Wrist Flexion ≠ Finger Extension *(Should not exceed zero)*

(a) SVEN Function for Myoelectrodes (b) SVEN Function for Force Sensors

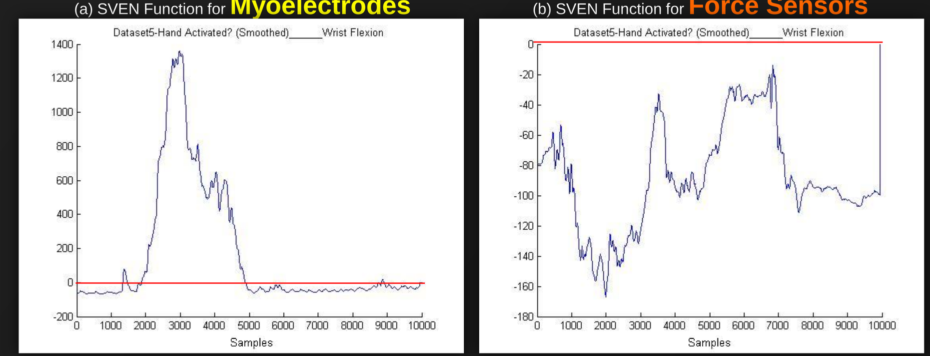


Figure 21 (a & b): Myoelectric and Force Sensor Finger Extension Smoothed SVEN Function (Blum, 2007)

Wrist Extension ≠ Finger Extension *(Should not exceed zero)*

(a) SVEN Function for Myoelectrodes (b) SVEN Function for Force Sensors

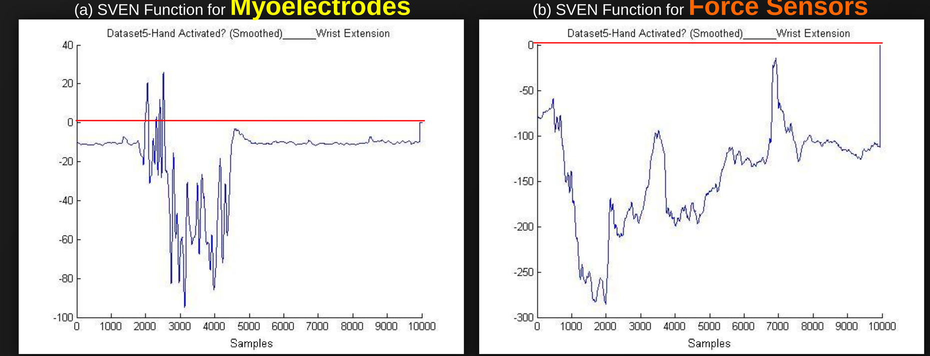


Figure 22 (a & b): Myoelectric and Force Sensor Finger Extension Smoothed SVEN Function (Blum, 2007)

conclusions

- No implantation → no risk of infection or sensor movement
- Pattern Recognition (SVEN function) mostly works without need for implantation
- Prosthesis can be easily removed
- Little interference + low cross-talk = high accuracy rates
- Sufficient voltage separation → eliminate post processing (voltage boundary can be measured using a comparator circuit with a fixed reference voltage)
- If post processing needed → SVEN algorithm needs perfecting
- Low cost

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methods and materials

1. Prosthetic Prototype

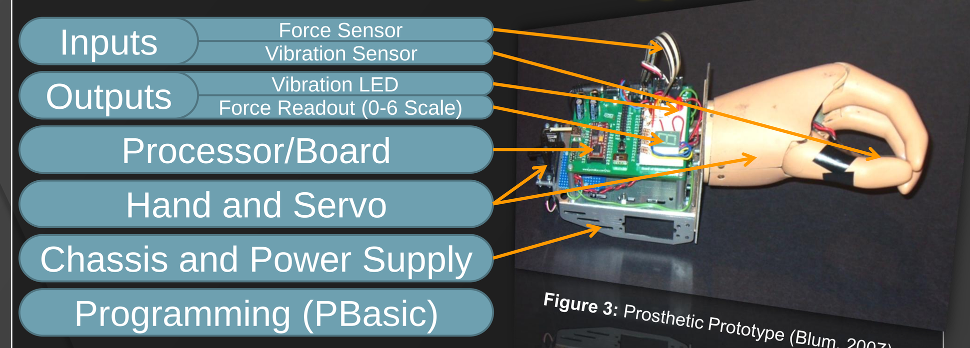


Figure 3: Prosthetic Prototype (Blum, 2007)

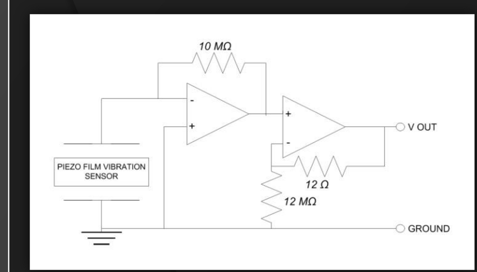


Figure 4: Vibration Sensor Circuit (Kyberd/Blum, 2007)

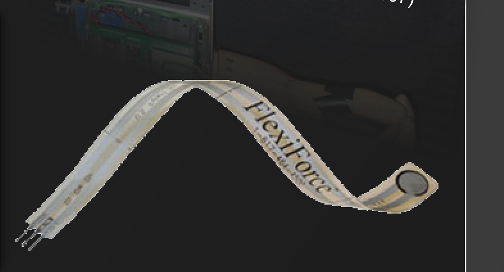


Figure 5: FlexiForce Sensor (tekscan.com, 2006)

2. Computer Interfaced Force Sensor Circuit

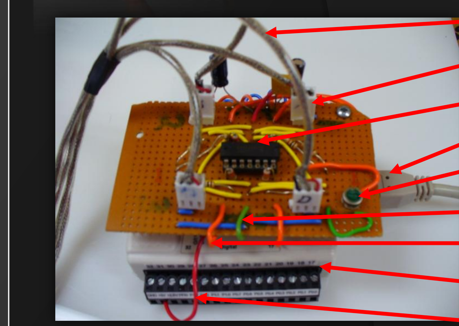
Forearm Muscles Used Shown in Green

#2-Extensor Carpi Ulnaris (finger extension)
#4-Supinator (wrist supination)
#6-Extensor Carpi Radialis Brevis (wrist extension)

Figure 6: Sensor Locations - Lateral Arm Aspect (Blum, 2007)

#1-Pronator Teres (wrist pronation)
#3-Flexor Digitorum Superficialis (finger flexion)
#5-Flexor Carpi Ulnaris (wrist flexion)

Figure 7: Sensor Location - Medial Arm Aspect (Blum, 2007)



- Sheathed FSR extension wires
- FSR connection to amplification board
- TLC2274 Quad Operational Amplifier
- USB cable for computer connection
- Variable resistor to adjust amplification
- Wire to ground
- Output from amplified signal to DAQ
- National Instruments 6008 USB DAQ
- +5V power, DAQ → amplification board

Figure 8: DAQ and amplification circuit board with four force sensors connected (Blum, 2007)

Figure 9: Internally mounted force sensors (Blum, 2007)

Figure 10: Cast fully equipped with sensors mounted (Blum, 2007)

Figure 11: Cast worn by Blum, Connected to DAQ (Blum, 2007)

Data Acquired from Muscles:

Action Data	Contraction and relaxation cycle of target muscle
Resting Calibration Data	Relaxation of all muscles
Active Calibration Data	Contraction of target muscle

3. Computer Input Analysis Program

Linear Discriminant Analysis via SVEN Function

(Torunn Midtgaard, 2006)

$$F(x) = Wx + w_0$$

$F(x) > 0$ ACTIVATION
$F(x) \leq 0$ NO ACTIVATION

When calibration muscle matches activation muscle, F(x) *should* be > 0

1. Raw voltage signals from force sensors tested using an oscilloscope, MATLAB, and National Instruments LabView Software to ensure minimal interference
2. User enters sample rate and acquisition duration
3. Calibration data acquired for each of the six muscles; each muscle dataset saved as file
4. Resting data acquired once as comparison point; dataset saved as file
5. Activation data acquired for each of the six muscles; each muscle dataset saved as file
6. Saved data files imported for analysis
   a. Resting data imported and stored in memory; graph exported to image file
   b. Activation data imported and stored in memory; graph exported to image file
7. All six calibration data sets compared to the six action data sets, resulting in 36 outcomes. First, all six calibration data sets and resting data compared using SVEN Function. Results again compared via SVEN Function to activation data to determine if activation has occurred.
8. A SVEN graph, a smoothed SVEN graph, and a Digital On/Off graph are drawn and exported
9. Calibration graphs visually compared with their associated action data to determine if muscle differentiation occurred
10. The Digital On/Off signal can be used to activate a prosthesis