Implantable Muscle Powered Piezoelectric Energy Harvesting System for Medical Devices

Kulkarni Shriram Krishn
M.Tech (SMD),
Smart Materials, Systems and Structures Lab,
Dept. of Mechanical Engineering,
Indian Institute of Technology – Kanpur.

Thesis Supervisor : Dr. Bishakh Bhattacharya

CONTENTS

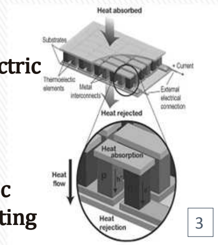
Review of Muscle powered Implantable Technologies

Technologies for Transduction

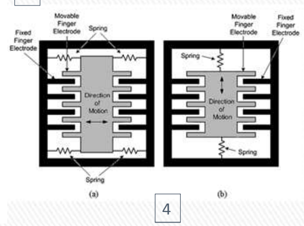
1

2

1. Piezoelectric Energy Harvesting
2. Electromagnetic Energy Harvesting
3. Thermoelectric Energy Harvesting
4. Electrostatic Energy Harvesting



3



4

Piezoelectric Effect

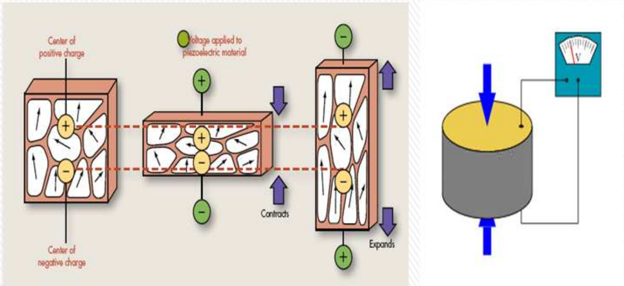


Fig.1: Piezoelectric Effect

Energy Harvester Loading Configurations

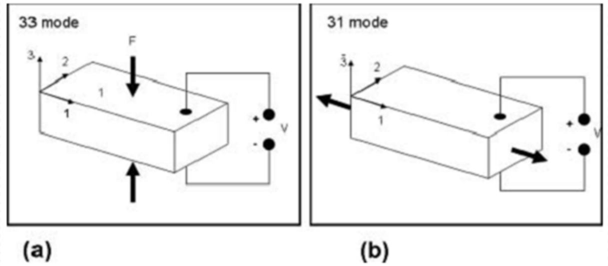
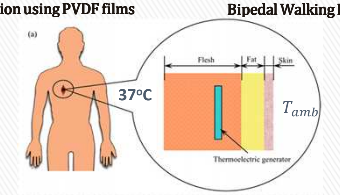


Fig.2 : Piezoelectric operation modes (a) 33-mode (b) 31-mode

Possible Power Sources for Implants

Heel Strike Utilization using PVDF films

Bipedal Walking Motion harvesting



Difference between core body temperature and atmospheric temperature

Muscle Power based Energy Harvesting - Introduction

- Skeletal muscle contains a significant amount of chemical energy
- Estimate of the sustained out put power of skeletal muscle producing isotonic contractions is 1 mW/gram
- The mass of human limb and trunk muscles ranges from 10 to 1000 grams
- Maximum Power available for conversion could be around 1 W
- Daily Activities produce frequent isotonic contractions of muscles which can be used for energy capture

Muscle Power Based Energy Harvesting - A Review

- Piezoelectric PVDF film patch on the intercostal muscles of the rib-cage of a dog (Hausler et al. 1984)
  - produce a voltage up to 18V and 17μW of power
- An investigation into the power production capabilities of human body functions and motions (Starner et al. 1996)
- Energy Harvesting using Blood Pressure (Ramsey et al. 2001)
- Shoe-mounted Piezoelectric Harvester (Kymissis et al.)
  - PVDF Bimorph, 1.3mW power, 18 V voltage produced
- Piezoelectric Energy Harvester using Human Knee motion
- Use of externally stimulated muscle producing isotonic contractions for energy harvesting

Piezoelectric Harvesting Using Muscles

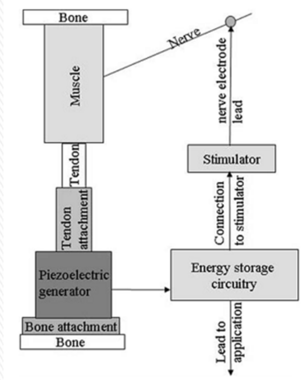


Fig. 5 – Muscle powered piezoelectric harvester[2]

- Convert tensile force produced by stimulated muscle contractions into compressive force that is applied to the piezoelectric material
- Portion of resulting charge will be used to power the nerve stimulations and remaining charge will be available to power the targeted application
- External stimulation can cause inconvenience to the host

Power Output for Various Muscles

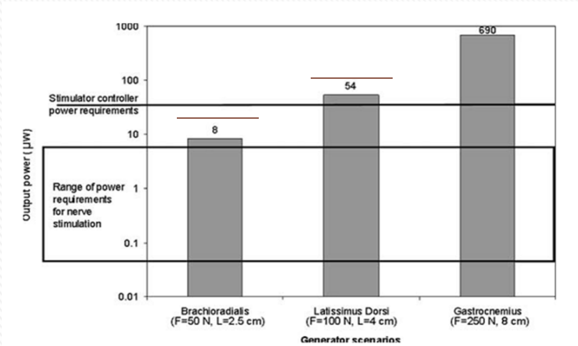


Fig. 6 – Muscles used for powering piezoelectric harvester with stimulator power outlined[3]

Simulation Work

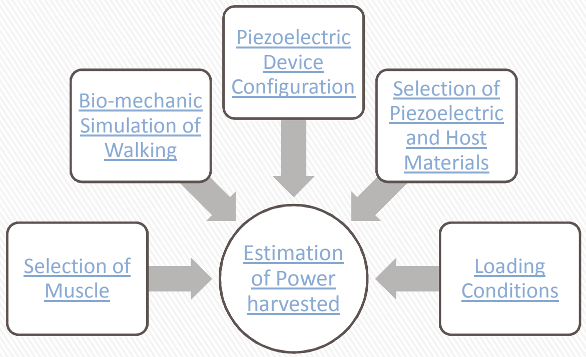
Introduction

- Use of Piezoelectric devices to directly convert muscle movement force generated from a continuous operation into electrical energy, without externally stimulating the muscle.
- Objective is to produce more power than that required for the working of implantable medical devices. The power requirements of some of these devices are,

Device	Power (W)	Device	Power
Implantable Pacemakers	4.8×10^{-6}	Operational Amplifiers	0.2 ~ 10 mW
Neural Stimulators	1.88×10^{-3}	ADC	0.3 ~ 3 mW
Glucose Sensors	4.8×10^{-6}	Wireless Transmitter	0.4 ~ 3 mW
Insulin Pumps	4.8	Oscillator	2 µW ~ 5 mW

Table 1: Power Requirement of various IMD's and Auxiliary devices[1]

Simulation Work Details



Selection of Muscle

- Based on Amount of Force produced
  - Depends on frequency of use and dimensions of the muscle
- Based on Location
  - Location near skin will be good for Implanting purposes
- Based on Muscle size, shape and amount of Contraction
  - More surface area
  - Pennation angle
- Comfort of the Host

Selection of Muscle

- Muscles with continuous operation
  - Respiratory muscles
    - Inspiratory muscles like the Diaphragm, External Intercoastals, Parasternal, Sternomastoid and scalene muscles
    - **Expiratory muscles** like the Internal intercostal, Rectus Abdominis, External and Internal Oblique and Transverse Abdominis muscles
- Muscles used in daily activity like walking
  - Gastrocnemius and its variants (i.e. Medial and Lateral)
  - Hamstring (Bicep Femoris and Semitendinosus)
- Muscles possibly involved in both the activities e.g. Rectus Abdominis and External Oblique

Selected Muscles for Study

- Lateral Gastrocnemius and Medial Gastrocnemius
- Semitendinosus and Biceps Femoris (Hamstring)
- Rectus Abdominis and External Oblique

Purposes of Bio-Mechanic Simulation

- Accurate estimation of muscle forces in the sagittal plane, which can effectively be used for energy harvesting
- Supplements the selection of muscle by suggesting the level of activity in the muscles involved

Bio-Mechanic Simulation Details

- Use of software LifeMod (A Bio-mechanic simulation add-on for MSC-Adams/View)
- Selected a male model with Indian Standard (174cm height and 74 kg. of weight)
- The software itself decides the appropriate length of muscles and skeleton length corresponding to this model
- Motion capture data for 3.3 seconds included in the software of walking activity has been used

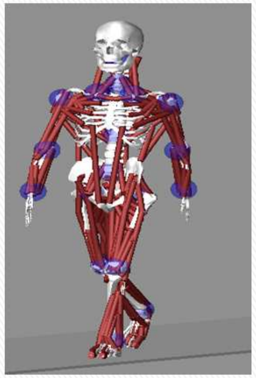
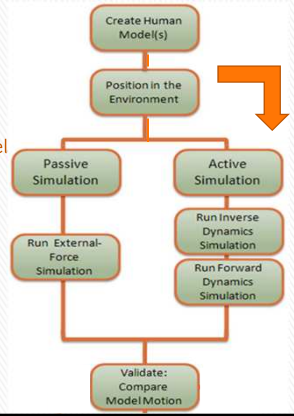


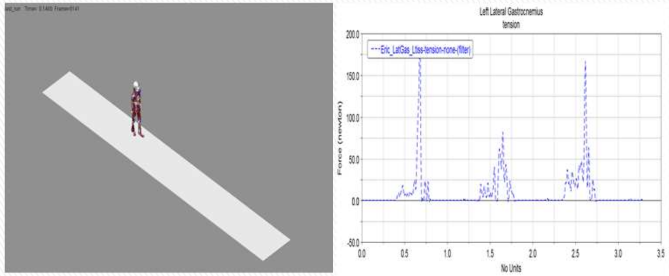
Fig. 7 – Bio-mechanic Simulation of a walking person

Bio-Mechanic Simulation Details

- The creation of human models begins by
  - Base human segment set,
  - Joints in the body,
  - Soft Tissues i.e. Muscles,
  - Contact elements between the model and the environment.
- Joints and soft tissues to be trained in an Inverse Dynamics Simulation
- Trained joints and soft tissues are then installed on the model to perform a Forward dynamics simulation



Bio-Mechanic Simulation Video



Bio-Mechanic Simulation Results

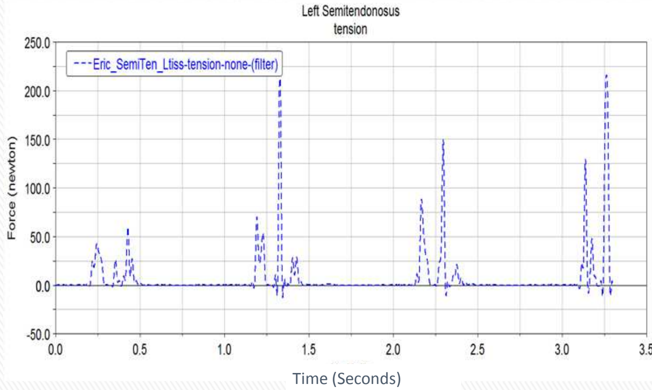


Fig. 8 – Force in Left Semitendinosus during walking

Bio-Mechanic Simulation Results

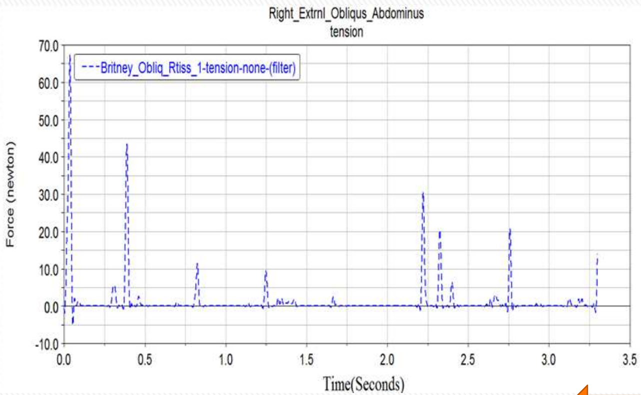


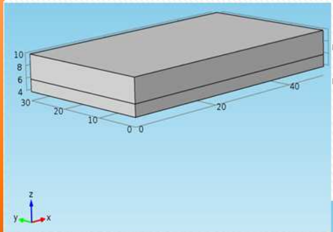
Fig. 9 – Force in Right External Oblique during walking

Piezoelectric Device Configurations

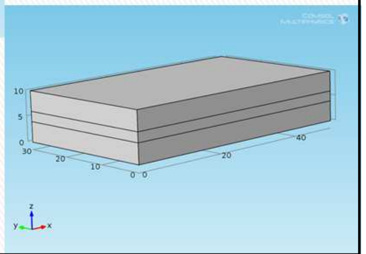
- Size depending on Muscle Physiological Cross Sectional Area (PCSA) and free length.
- PCSA data for some muscles:

Muscle	Maximum PCSA (cm^2)
Lateral Gastrocnemius	35
Medial Gastrocnemius	33.5
Bicep Femoris	36
Semimembranosus	72

Piezoelectric Device Configurations

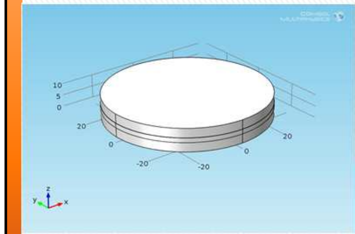


- **Unimorph**
- The size is chosen as 50mm x 30mm x [(4mm x 1 piezo) + (2mm x host)]

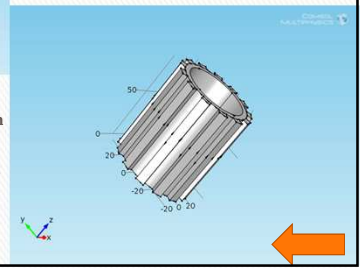


- **Bi-morph**
- The size is chosen as 50mm x 30mm x [(4mm x 2 piezo) + (2mm x host)]

Piezoelectric Device Configurations



- **Disk**
- The size is chosen as 66.6mm diameter corresponding to least PCSA and 1cm height



- **Tube with Piezo strips along the Length**
- The size is chosen as 80mm length and 13 piezo patches of Cross section 8 mm x 5 mm

Piezoelectric Materials Used

- **PZT Ceramics (in increasing order of hardness)**
  - PZT-2
  - PZT-5A
  - PZT-5H
- **PVDF film**

Selection of Host

- **Bio-inert Materials**
  - PMMA
  - PEEK
- **Ordinary Materials**
  - Metal – Al
  - Teflon

Loading Conditions

» **Based on mode of attachment between the Piezoelectric device and the muscle**
- > Insert
  - + Muscle force acting as uniformly distributed pressure over the device surface
- > Patch
  - + Muscle force as body force in a muscle model, to which the patch is connected

» **Based on muscle pennation**
- > Change in displacement and Piezoelectric device output with Pennate angle of the muscle
  - + Muscle force applied at pennation angle

Estimation of Power Produced

» **Voltage Production**
- > Terminal Voltage
- > Peak Voltage

» **Optimum Resistance for the device**

» **Energy Harvesting Circuit**

Voltage Results

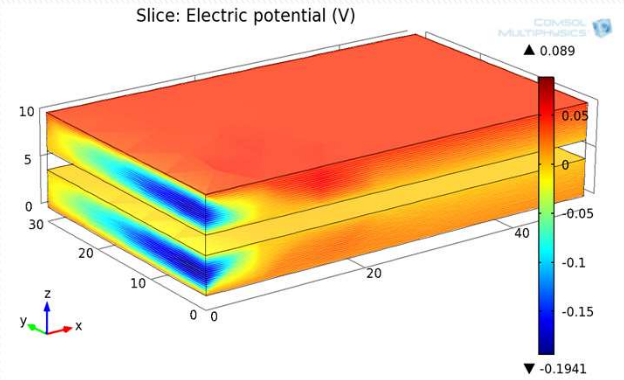
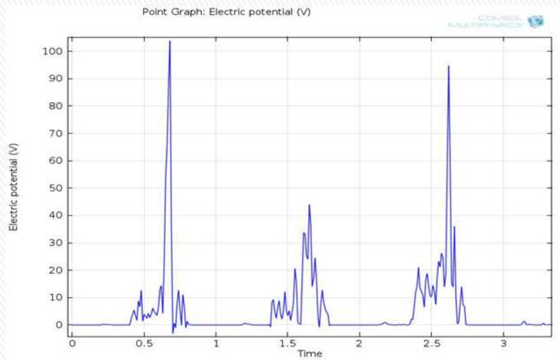


Fig. 12– Voltage generated after 3.3 seconds in PZT-5H for Lateral Gastrocnemius muscle force

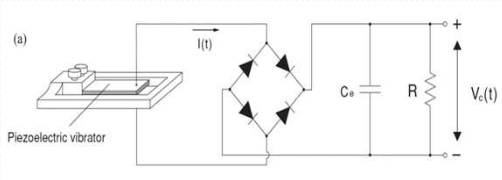
Voltage Results

» **Voltage variation with time on the cantilever tip**



Energy Harvesting Circuit

» Full wave Rectifier and a Capacitor for reducing Ripples



» $V_{rms} = \frac{V_{peak}}{\sqrt{2}}$ in Volts for an Ideal Rectifier

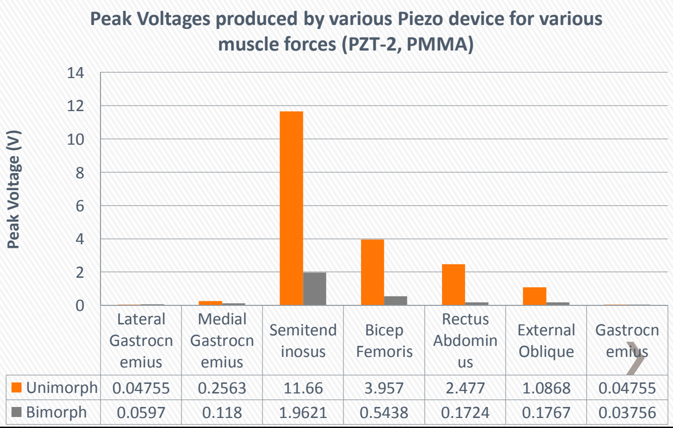
» $V_{dc} = \frac{2.V_{peak}}{\pi}$ in Volts for an Ideal Rectifier

Voltage Results

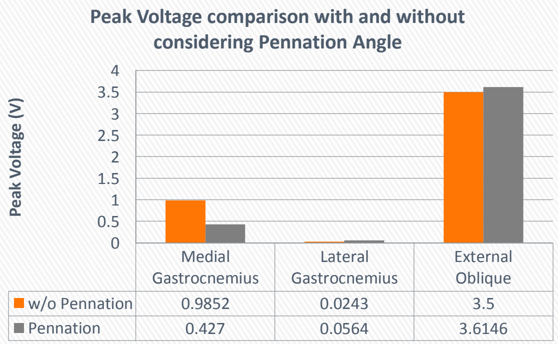
» Unimorph (Piezo material : PZT2, Host Matl. : PEEK)

Muscle	Terminal Voltage (V)	Peak Voltage (V)	V_{rms} (V)	V_{dc} (V)
Left Lateral Gastrocnemius	0.011	-0.1301	-0.09199	-0.08279
Left Medial Gastrocnemius	-0.0212	0.4236	0.29953	0.269564
Left Semimembranosus	-1.1959	20.372	14.40518	12.964
Bicep Femoris	-0.9425	11.868	8.391943	7.552364
Rectus Abdominus	-1.5075	29.693	20.99612	18.89555
External Oblique	0.3091	-6.2197	-4.39799	-3.95799
Gastrocnemius	-0.065	0.1301	0.091995	0.082791

Voltage Results Comparison



Comparison of Voltage Results for Pennate Muscles



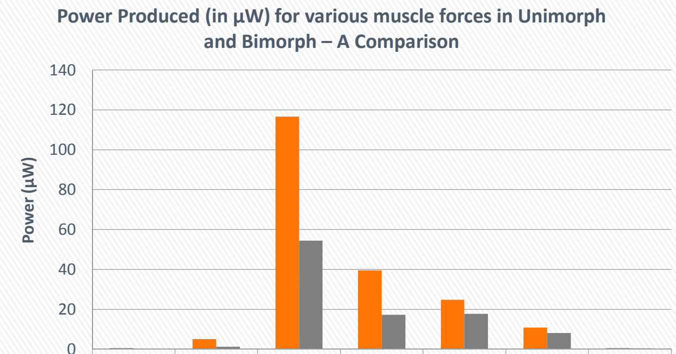
Optimum Load Resistance

» **Impedance matching at Load frequency or natural frequency**

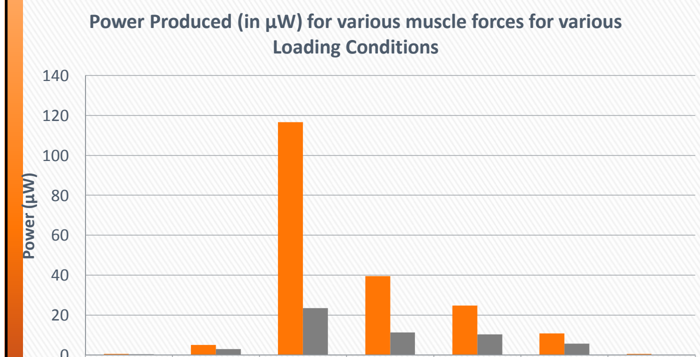
» $$R_L = Z_d = \frac{1}{\omega_N . C_P} + \frac{1}{\omega_N . C_e}$$

» **Where ,**

- R_L is the Load Resistance
- Z_d is the Impedance of the piezoelectric device
- ω_N is Natural Frequency of the harvester
- C_P is Internal Capacitance of Piezoelectric material
- C_e is Ripple effect reducing Capacitor



	Lateral Gastrocnemius	Medial Gastrocnemius	Semitendinosus	Bicep Femoris	Rectus Abdominis	External Oblique	Gastrocnemius
Unimorph	0.4755	5.0412	116.6	39.57	24.77	10.868	0.4566
Bimorph	0.05597	1.18	54.389	17.214	17.675	7.9984	0.3214



	Lateral Gastrocnemius	Medial Gastrocnemius	Hamstring	Rectus Abdominus	External Oblique	Bicep Femoris	Gastrocnemius
Insert	0.4755	5.0412	116.6	39.57	24.77	10.868	0.4566
Patch	0.3251	2.8773	23.452	11.214	10.356	5.6321	0.2145

Experimental Work

» **Applying Forces to Piezoelectric devices**

- Base Excitation
- Tip Excitation

Experimental Model Details

» **Piezoelectric material**
  > Poly Vnyl Di Fluoride (PVDF)

» **Base Material**
  > Teflon

» **Dimensions**
  > Base Size : 7 cm x 3 cm x 0.7 cm
  > Film Size : 4 cm x 3 cm

» **Loading Conditions**
  > Base Excitation
  > Tip Excitation

Experimental Results

Base Excitation Voltage for Left Gastrocnemius force

	CH1 Value
Max [V]	416.00m
Min [V]	-144.00m
Pk-Pk [V]	560.00m
High [V]	416.00m
Low [V]	-56.00m
Amplitude [V]	472.00m
Average [V]	0
RMS [V]	32.00m
Period [s]	173.10m
Frequency [Hz]	5.78
Cycle Avg [V]	0
Cycle RMS [V]	32.00m

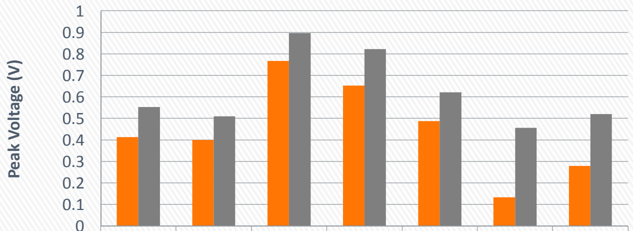
Experimental Results

Tip Excitation Voltage for Left Gastrocnemius force

	CH1 Value
Max [V]	32.00m
Min [V]	-36.00m
Pk-Pk [V]	68.00m
High [V]	0
Low [V]	-24.80m
Amplitude [V]	24.80m
Average [V]	-7.20m
RMS [V]	17.60m
Period [s]	15.20u
Frequency [Hz]	65.79k
Cycle Avg [V]	-800.00u
Cycle RMS [V]	19.20m

Comparisons

Peak Voltages produced by various Piezo device for various muscle forces (PZT-2, PMMA)



	Lateral Gastrocnemius	Medial Gastrocnemius	Semitendinosus	Bicep Femoris	Rectus Abdominus	External Oblique	Gastrocnemius
Tip Exct.	0.4123	0.3998	0.7666	0.6523	0.4872	0.1324	0.2791
Base Exct.	0.5523	0.5101	0.8965	0.82145	0.621	0.4562	0.5201

Conclusion

- **We can confirm the energy harvesting capability of the human muscles and thus they can be used for empowering Implantable Medical Devices.**
- **Use of Unimorph with the help of PZT-2 and Bio-inert materials (PMMA, PEEK) offers highest power around 120 µW.**
- **Piezoelectric device in Insert condition produces more power than a patch, but is medically invasive.**
- **It has been noted that a trade-off is required in terms of continuous extraction of low energy from respiratory i.e. continuous working muscles versus discontinuous extraction of high energy particularly from lower body muscles.**

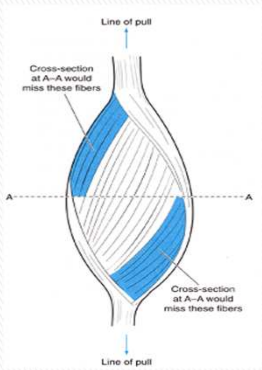
References

1. Dewei Jia., Jing *Liu. Human power-based energy harvesting strategies for mobile electronic devices.* Front. Energy Power Eng. China, 2009, 3(1), 27-46.
2. B.E. Lewandowski, K.L. Kilgore, K.J. Gustafsson, *Design Considerations for an Implantable, Muscle Powered Piezoelectric System for Generating Electrical Power,* Annals of Bio-medical Engineering, Vol. 35, No. 4, April 2007, pp. 631-641.
3. B.E. Lewandowski, K.L. Kilgore, K.J. Gustafsson*, In Vivo Demonstration of a Self-Sustaining, Implantable, Stimulated-Muscle-Powered Piezoelectric Generator Prototype,* Vol. 37, No. 11, Nov. 2009, pp. 2390-2401.
4. Anat Ratnovsky, David Elad. *Anatomical model of the human trunk for analysis of respiratory muscles mechanic,* Respiratory Physiology and Neurobiology, 148(2005), 245-262.

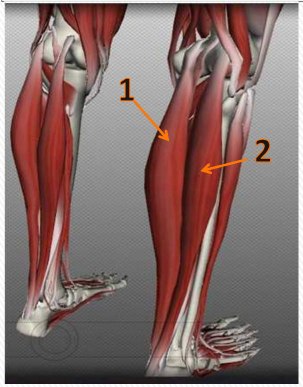
THANK YOU!!

The work presented here is selected for publication in **ACM Digital Library** and **IEEE Xplore** in the **Proceedings of International Conference on Rehabilitative and Assistive Technologies – Singapore 2012**

Physiological Cross Sectional Area (PCSA)



Lateral and Medial Gastrocnemius



» 1. Medial Gastrocnemius

» 2. Lateral Gastrocnemius

Piezoelectric Insert Placement

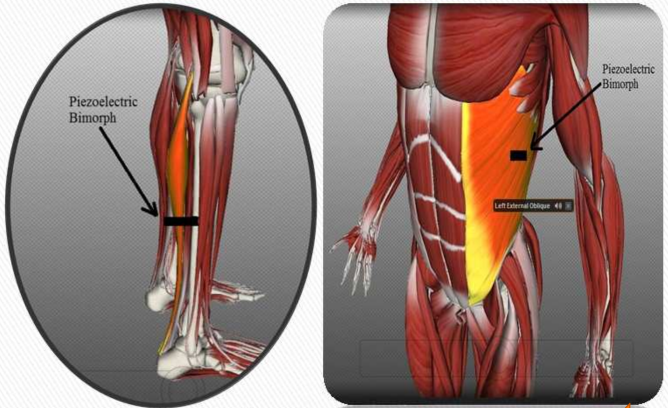
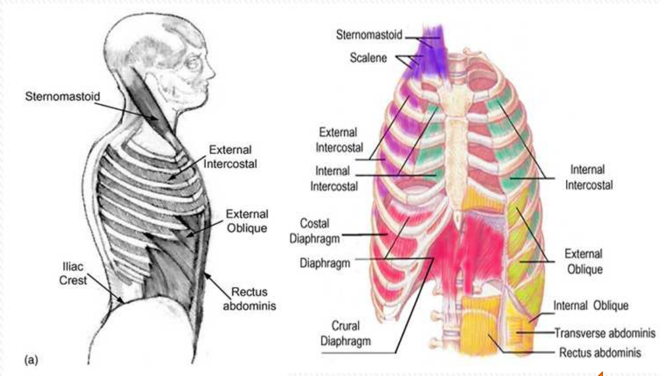
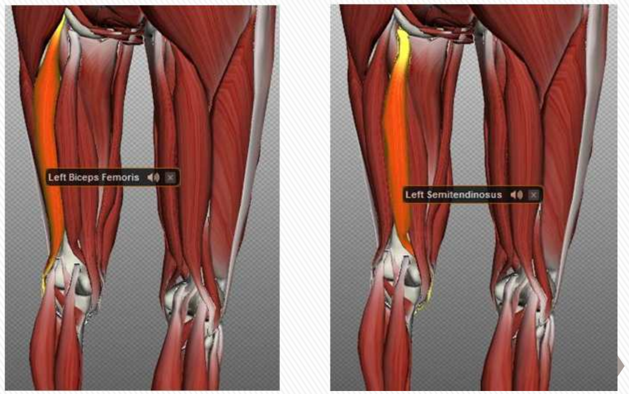


Fig. 11– Piezoelectric Device Placement in Lateral Gastrocnemius and in External Oblique

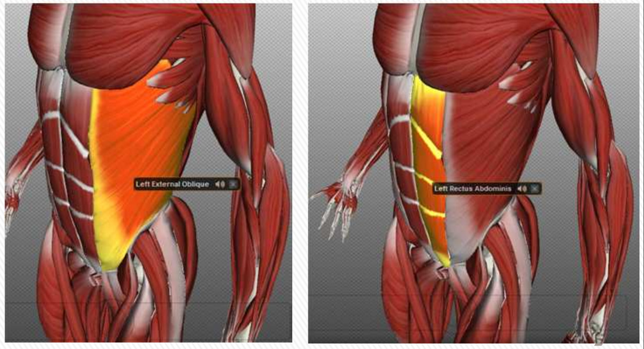
Respiratory Muscles



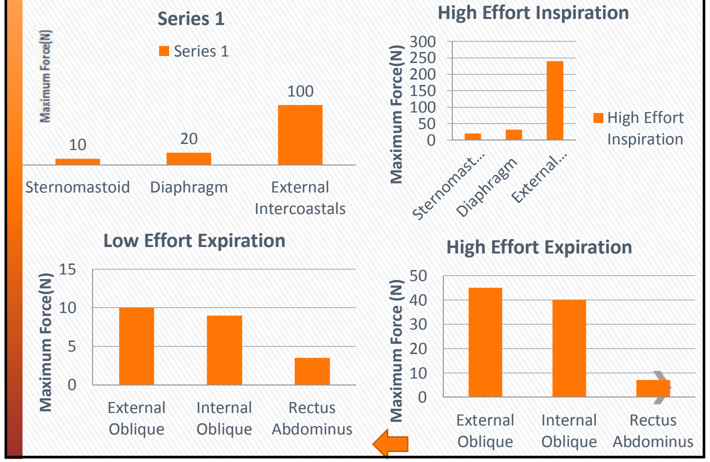
Hamstring



Respiratory Muscles

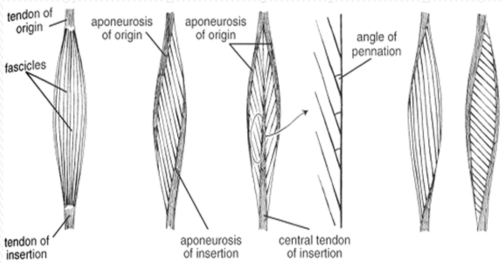


Forces during Respiration



Muscle Pennation

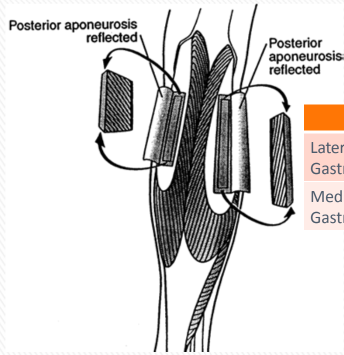
» Angle between line of action and the orientation of fibers



» Less displacement for a pennate muscle for same amount of force

Muscle Pennation

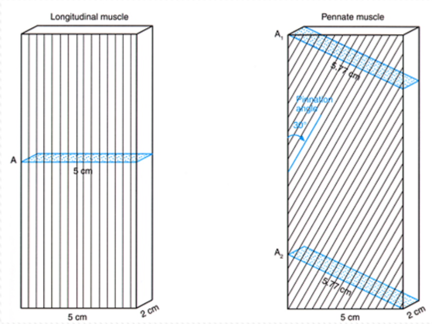
» Lateral and Medial Gastrocnemius pennation effect



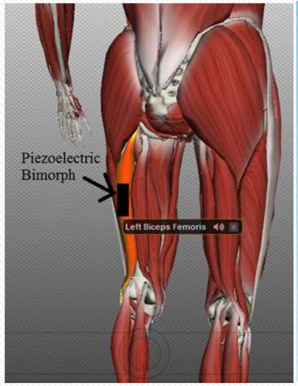
	At Rest (θ°)	At MVC(θ°)
Lateral Gastrocnemius	14.1~18.4	22.4~34.8
Medial Gastrocnemius	18.6~23.1	34.6~40.2

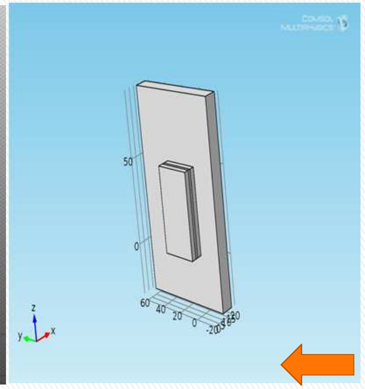
Muscle Pennation

» Mechanical Advantage or 'Gear Ratio' of pennate muscles

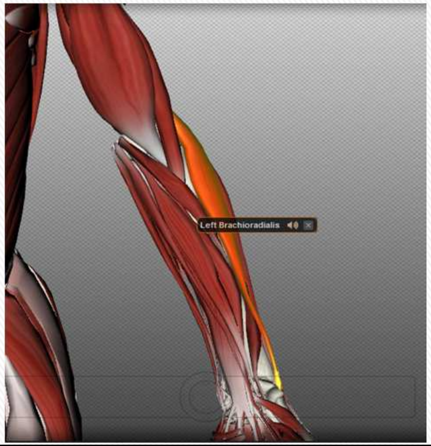


Piezoelectric Bimorph in Shear





Brachioradialis



Latissimus Dorci