An Implanted, Stimulated Muscle Powered Piezoelectric Generator

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NASA Glenn Research Center

A totally implantable piezoelectric generator system able to harness power from electrically activated muscle could be used to augment the power systems of implanted medical devices, such as neural prostheses, by reducing the number of battery replacement surgeries or by allowing periods of untethered functionality. The features of our generator design are no moving parts and the use of a portion of the generated power for system operation and regulation. A software model of the system has been developed and simulations have been performed to predict the output power as the system parameters were varied within their constraints. Mechanical forces that mimic muscle forces have been experimentally applied to a piezoelectric generator to verify the accuracy of the simulations and to explore losses due to mechanical coupling. Depending on the selection of system parameters, software simulations predict that this generator concept can generate up to approximately 700 μW of power, which is greater than the power necessary to drive the generator, conservatively estimated to be 50 μW. These results suggest that this concept has the potential to be an implantable, self-replenishing power source and further investigation is underway.

AN IMPLANTED, STIMULATED MUSCLE POWERED PIEZOELECTRIC GENERATOR

UTA Workshop on Piezoelectric Energy Harvesting

1/31/07

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Bioscience and Technology Branch

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COLLABORATIVE PROJECT

The Cleveland Functional Electrical Stimulation (FES) Center is dedicated to the advancement of neuro-augmentation and neuro-prosthetic solutions.

Collaborators:
Beth Lewandowski, NASA Glenn Research Center
Kevin Kilgore, Metro Health Medical Center
Kenneth Gustafson, Case Western Reserve University

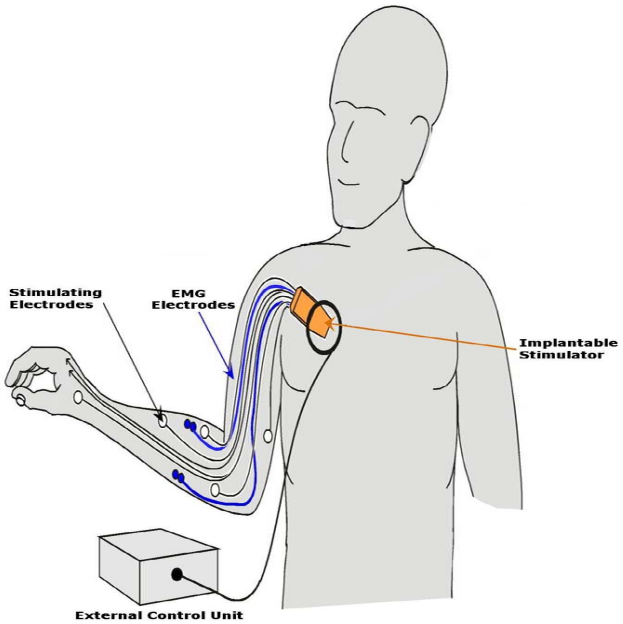
Metro Health Medical Center

Case Western Reserve University

NASA Glenn Research Center

RATIONALE FOR PROJECT

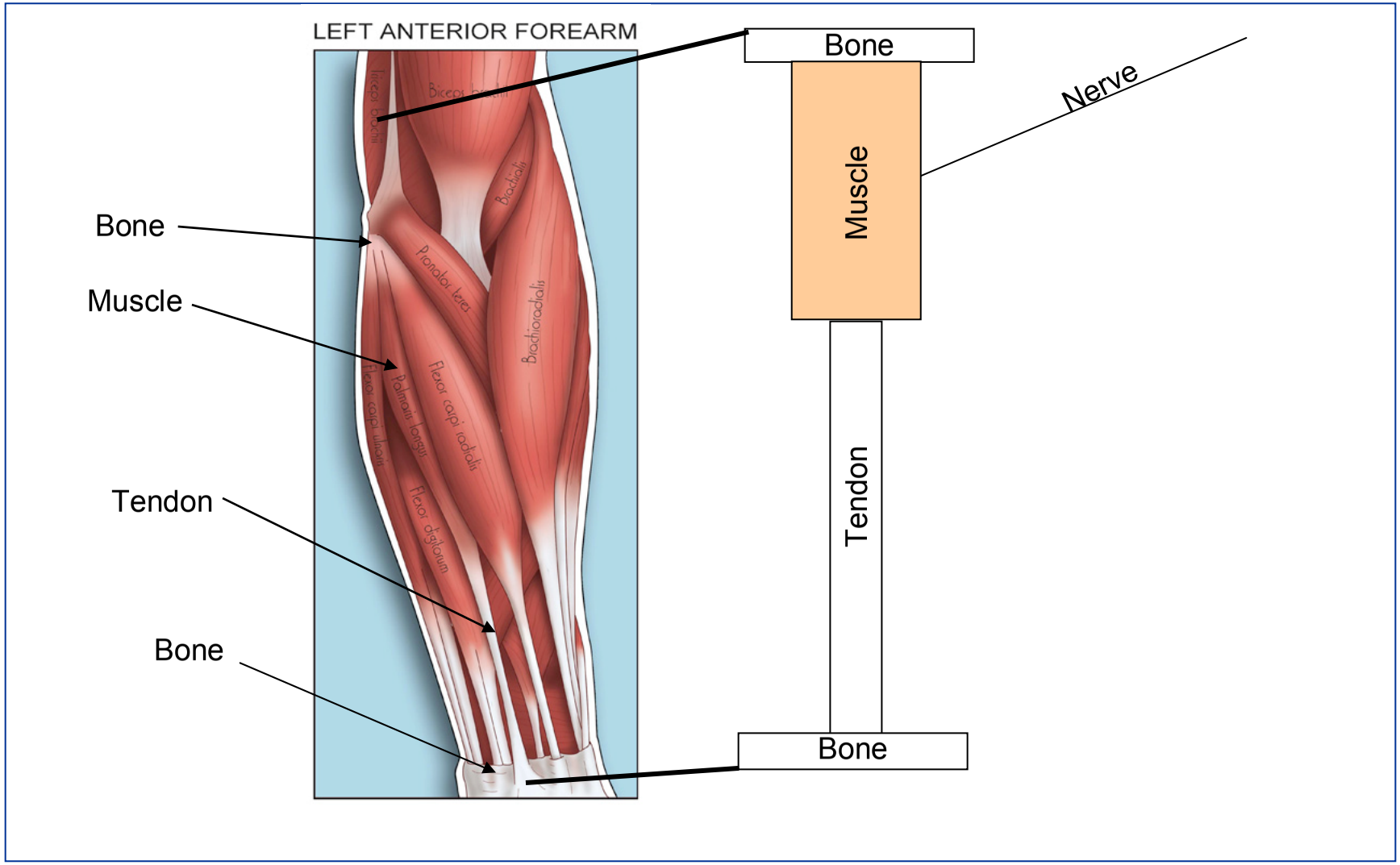
- Functional electrical stimulation (FES) is a method where electrical current is applied to the nervous system to restore or improve the function of a system compromised by paralysis
  - Motor function
  - Respiration
  - Bladder and bowel function
- Most FES devices are implanted into the body and need electrical power for operation.
- Current power sources include:
  - Implanted batteries
  - Transcutaneous power sources
- Areas for improvements:
  - Reduce replacement surgeries
  - Allow time without external equipment
    - Increase independence (allow FES use in a wet environment)
    - Reduce equipment malfunction (wire connections, coil misalignment)



PROJECT OBJECTIVE

Determine the feasibility of using stimulated muscle to power a self-sustaining, totally implantable power source for implanted FES devices.

PIEZOELECTRIC GENERATOR CONCEPT



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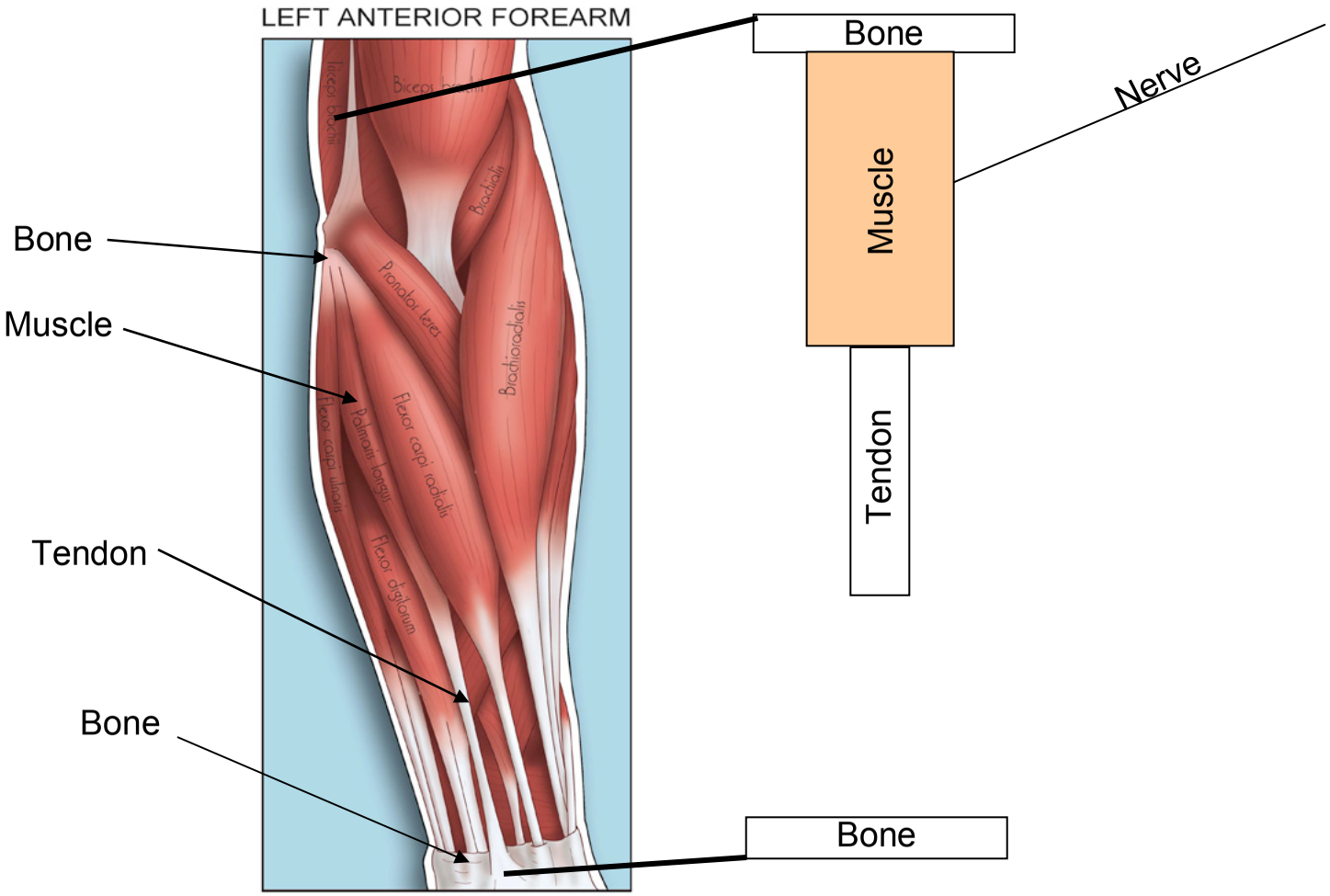

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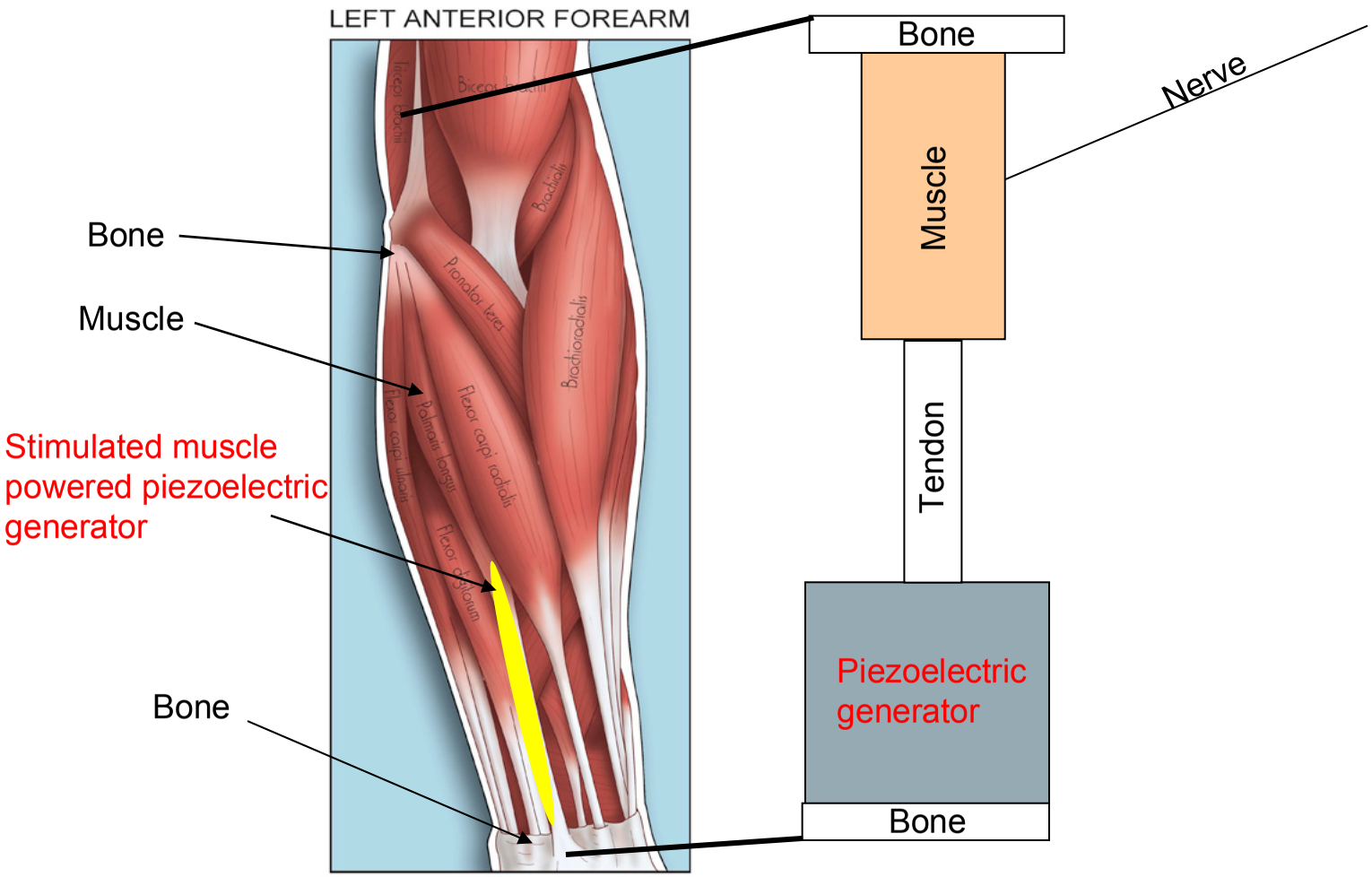

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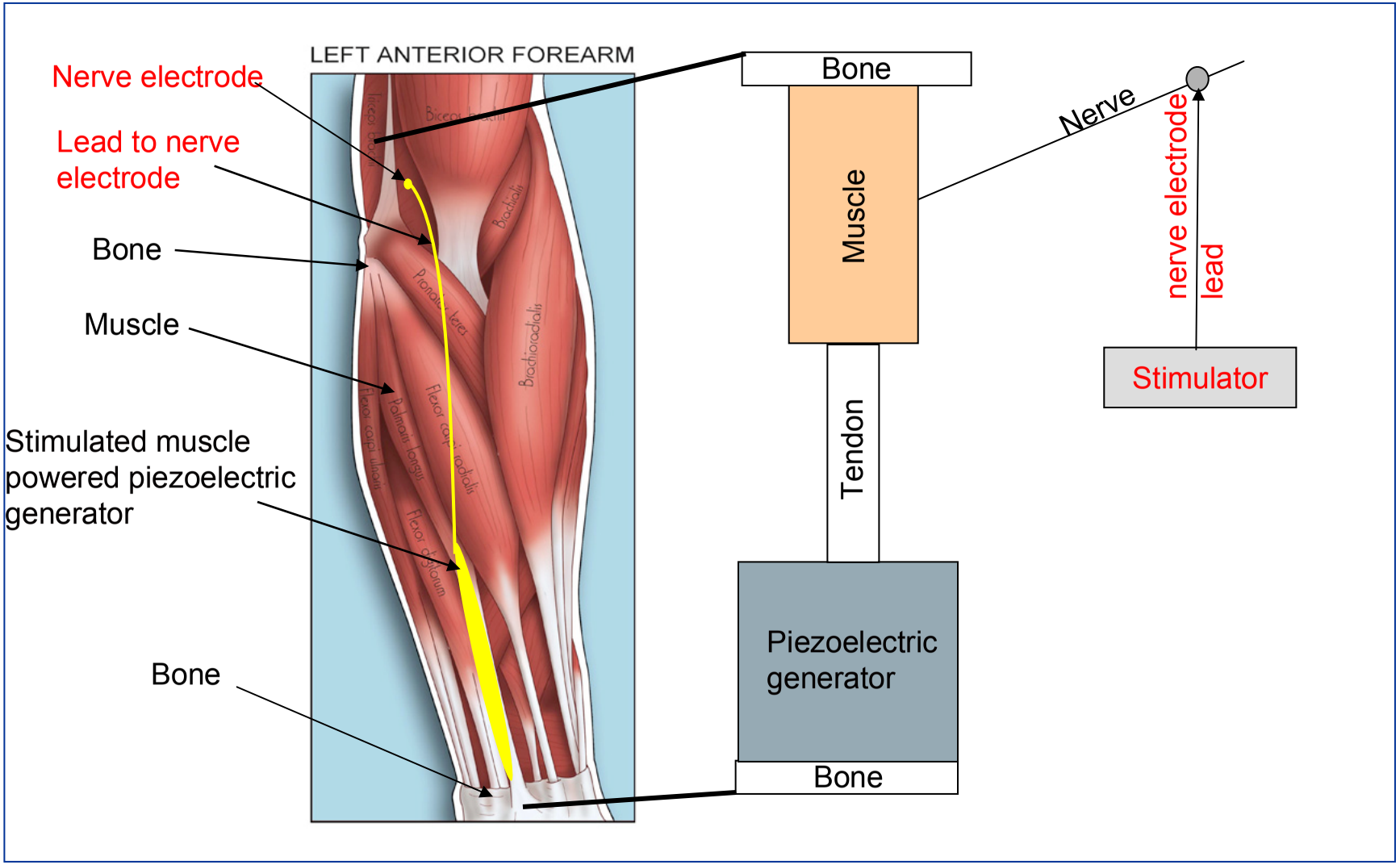

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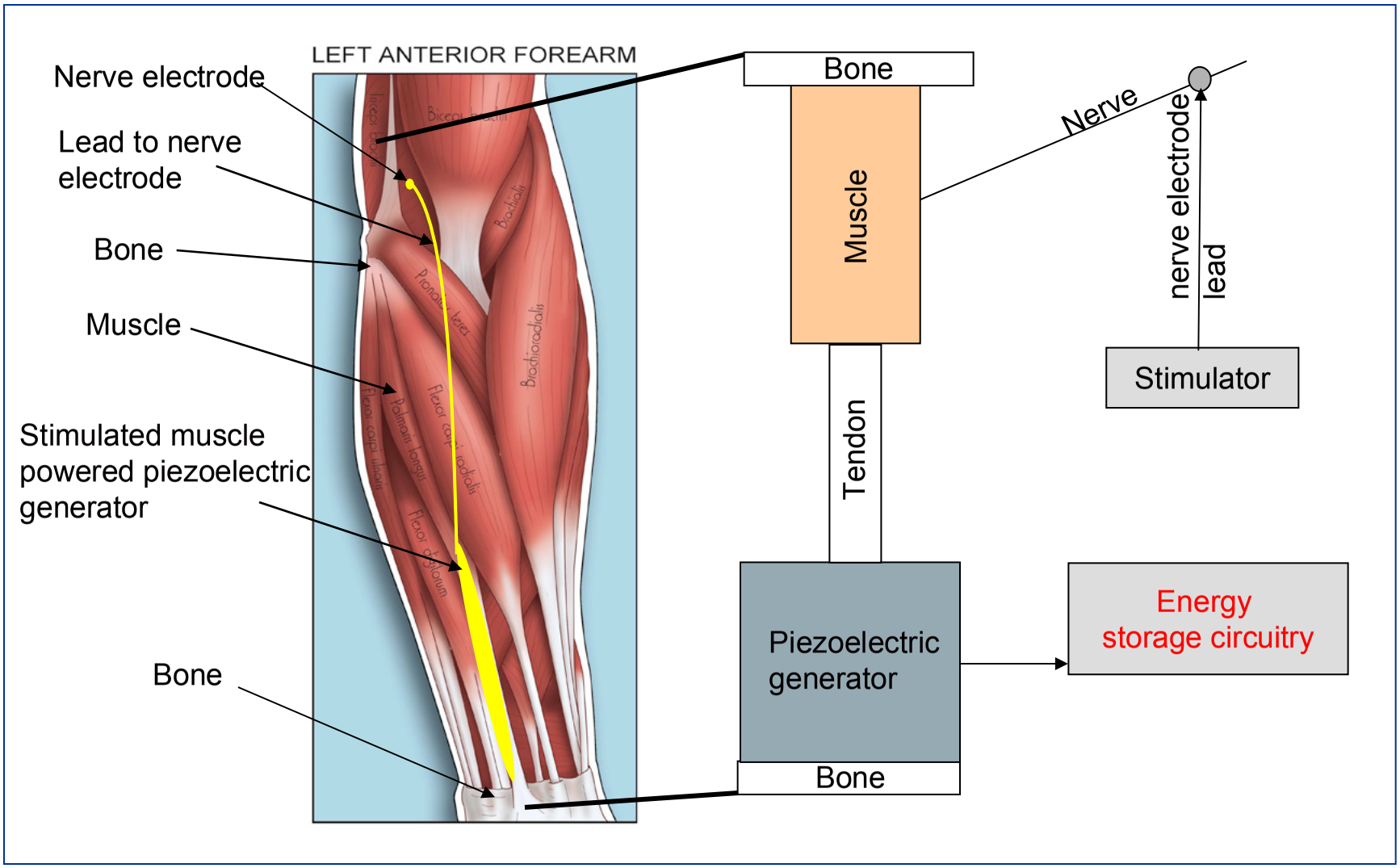

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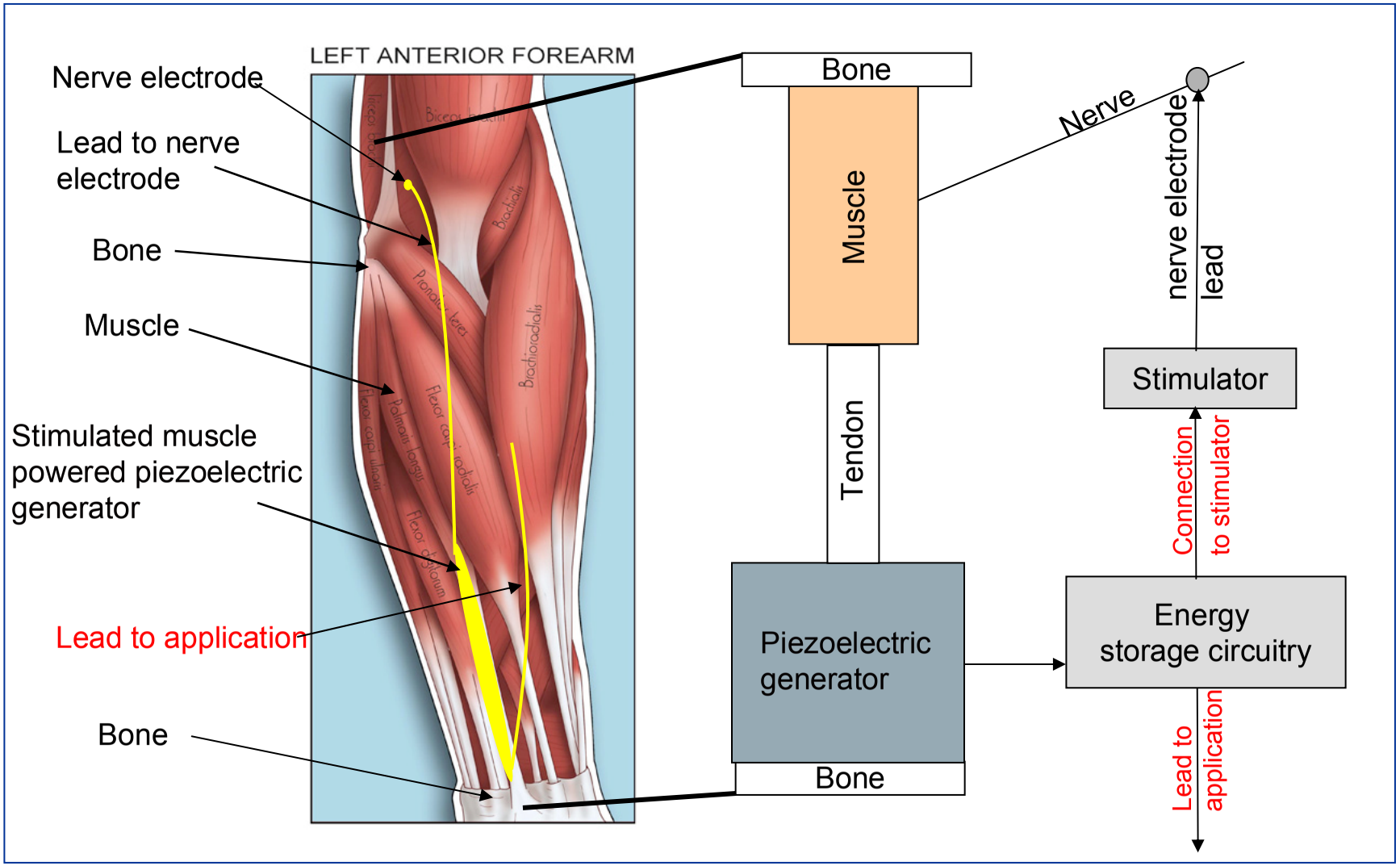


PROJECT UNIQUENESS

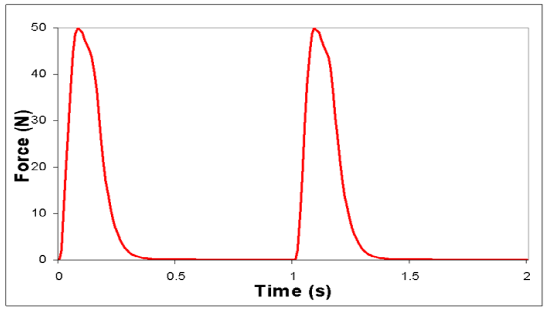
- The system uses no moving parts and contains a natural connection in series with the muscle tendon unit
  - Previous implanted generator designs that use motion for operation have suffered from reduced efficiency during chronic operation
- The system leverages the power amplification characteristic of muscle
  - More output power is available from a muscle than is needed for electrical stimulation of the motor nerve
  - Gain is achieved through chemical energy stored in the muscle
- For neural prosthesis application the concept uses a paralyzed muscle for which restoration of function is not anticipated.

STEPS TO DETERMINE FEASIBILITY

- A software circuit model was developed and used to:
  - Understand system parameters
  - Estimate output power
- Mechanical tests were conducted to:
  - Determine the accuracy of the software model
  - Test a mechanical holder for the piezoelectric generator
- Test in an acute animal model
  - Demonstrate force application with a physiological source
  - Demonstrate closed-loop system operation

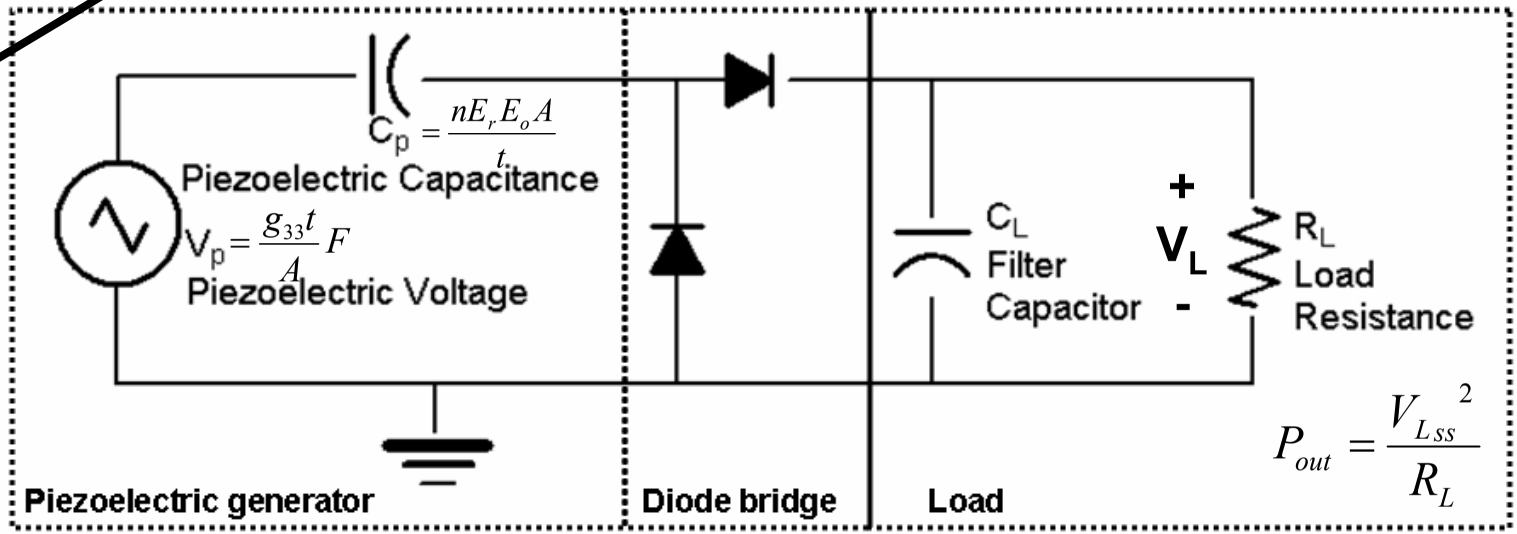
SOFTWARE MODEL OF SYSTEM

Input force from muscle

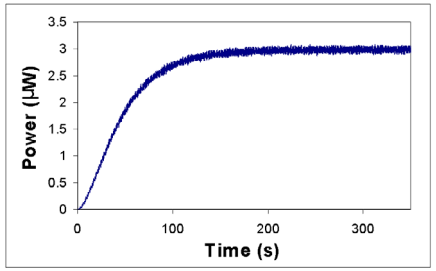


Generator and circuit

Load circuit



Output power

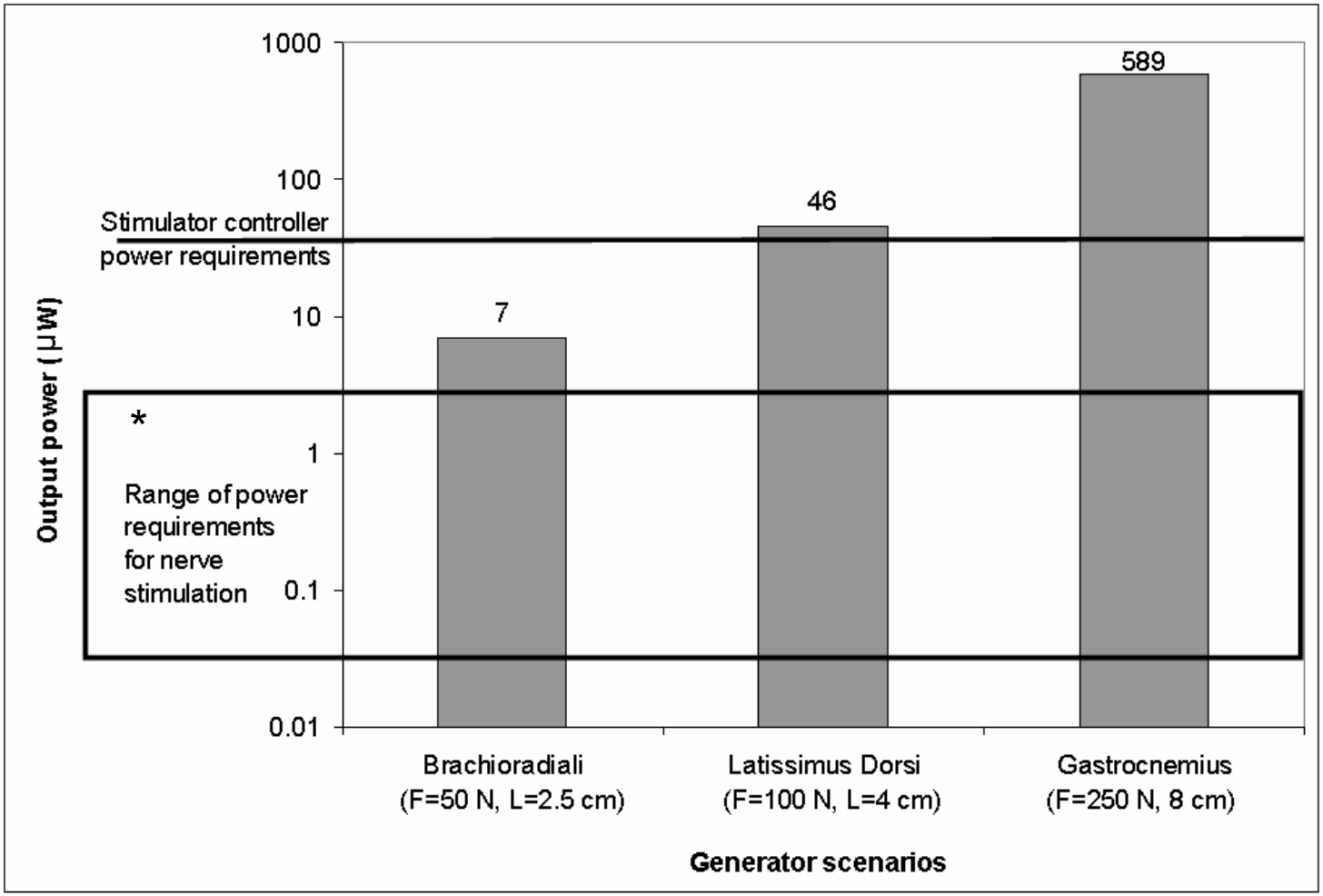


$$P_{out\,opt} = \frac{V_{pm}^2 f C_p}{4} = \frac{g_{33}^2 F_m^2 t n E_r E_o f}{4A}$$

SYSTEM PARAMETERS

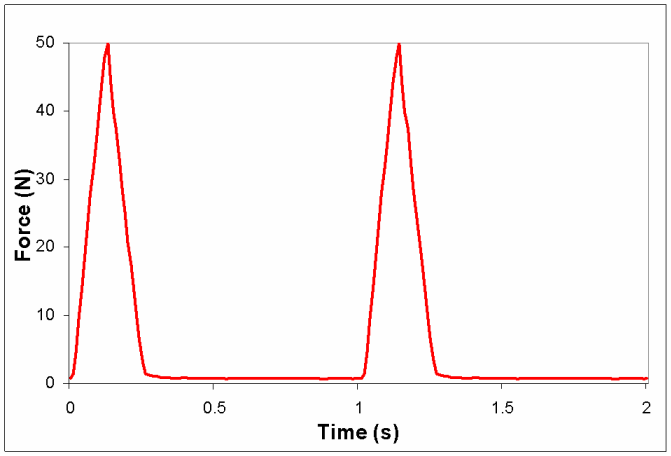
Parameter	Symbol	Maximize or minimize for max power	Physical or physiological constraints	Relationship with other parameters	Range of possible values
Piezoelectric constant	g_{33}	Maximize	Availability of material	g_{33} and E_r have an inverse relationship	14 – 54 mV*m/N
Dielectric constant	E_r	Maximize	Availability of material	$E_r = 13{,}187e^{-71g_{33}}$	400 - 5800
Number of layers	n	Maximize	Space available for implantation	Can be used to set output voltage	25 - 1500
Thickness of one layer	t	Maximize	Space available for implantation	Can be used to set output voltage	0.13 – 2 mm
Length	L	Maximize	Will be approximately the length of the tendon	L = n*t, Must maintain a proper ratio with A	50 – 200 mm
Area	A	Minimize	Must be able to be machined	Must maintain a proper ratio with L	0.06 – 4 cm^2
Peak input force	F_m	Maximize	Size of muscle and stimulation parameters	F_m and f have an inverse relationship	10 – 250 N
Frequency of input force	f	Maximize	Muscle fatigue	F_m and f have an inverse relationship	0.5 – 2 Hz

PREDICTED OUTPUT POWER FOR THREE SCENARIOS



* High value calculated from 500 μs, 1 mA pulses across 1000 Ω at 30 Hz for 250 ms per contraction at 1 Hz. Low value is calculated from single pulses of 500 μA for 200 μs across 1000 Ω at 1Hz.

MECHANICAL TEST PROCEDURE



A MTS machine was used to apply input force at 1 Hz with peak values of 25, 50, 100, 150, 200 and 250 N to a lead zirconate titanate (PZT) piezoelectric stack generator (part number T18-H5-104, Piezo Systems, Inc. Cambridge, MA).

Compressive force was applied directly to the stack and tensile force was applied to a holder for the piezoelectric stack.

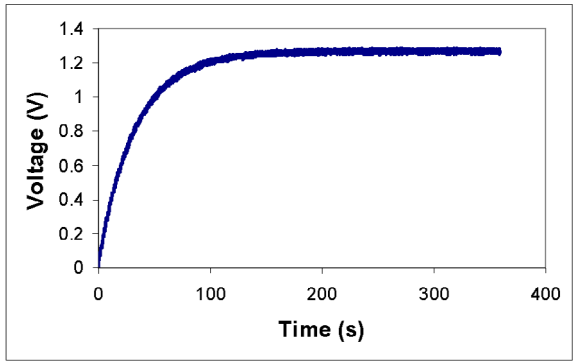
In vivo, the holder will attach the piezoelectric stack to the tendon and to the bone.

The tensile force from the muscle will pull on the holder, which will cause compressive force to be applied to the stack between the two plates.

Mechanical tests were performed to determine if there are losses associated with the mechanical coupling

MECHANICAL TEST RESULTS

The stack was connected to the diode bridge and load circuit and output voltage was measured across the load resistor

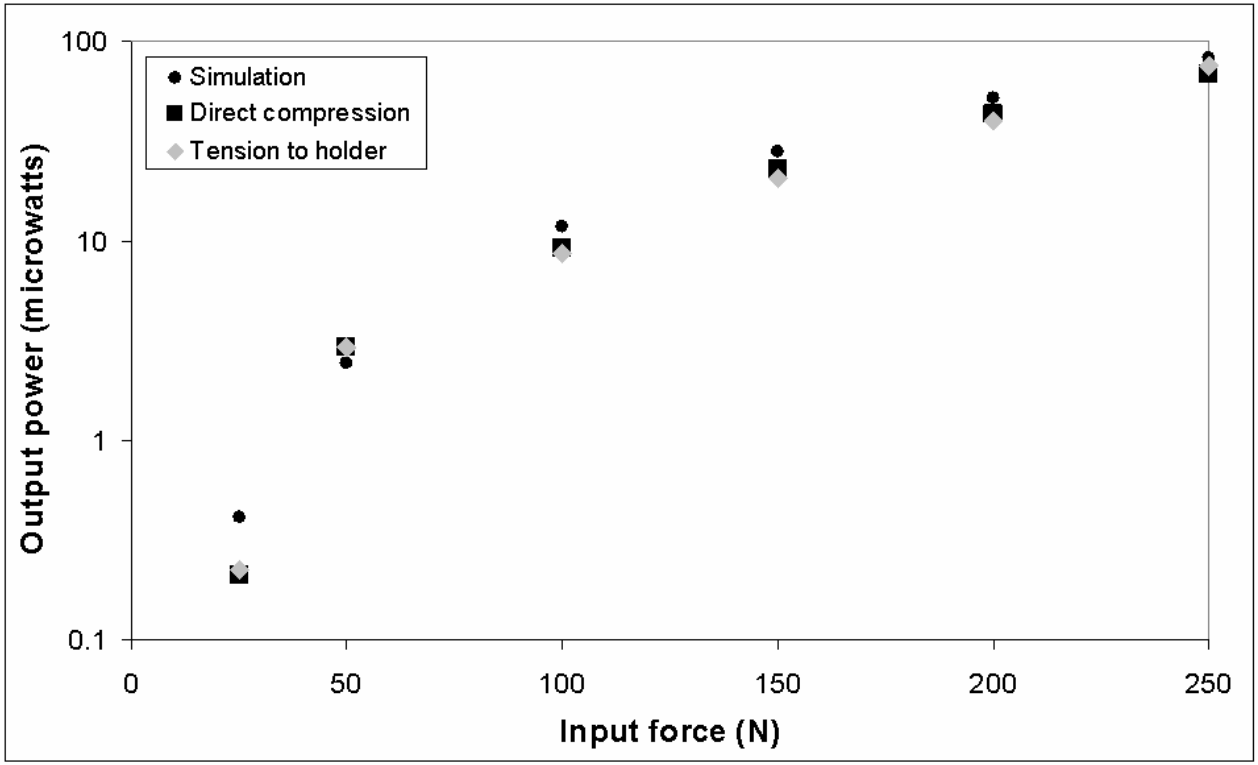


The steady state voltage was used to calculate output power

$$P_{out} = \frac{V_{L_{ss}}^{2}}{R_L}$$

Simulation results match experimental results, verifying accuracy of model

Very little mechanical coupling losses occur when using holder

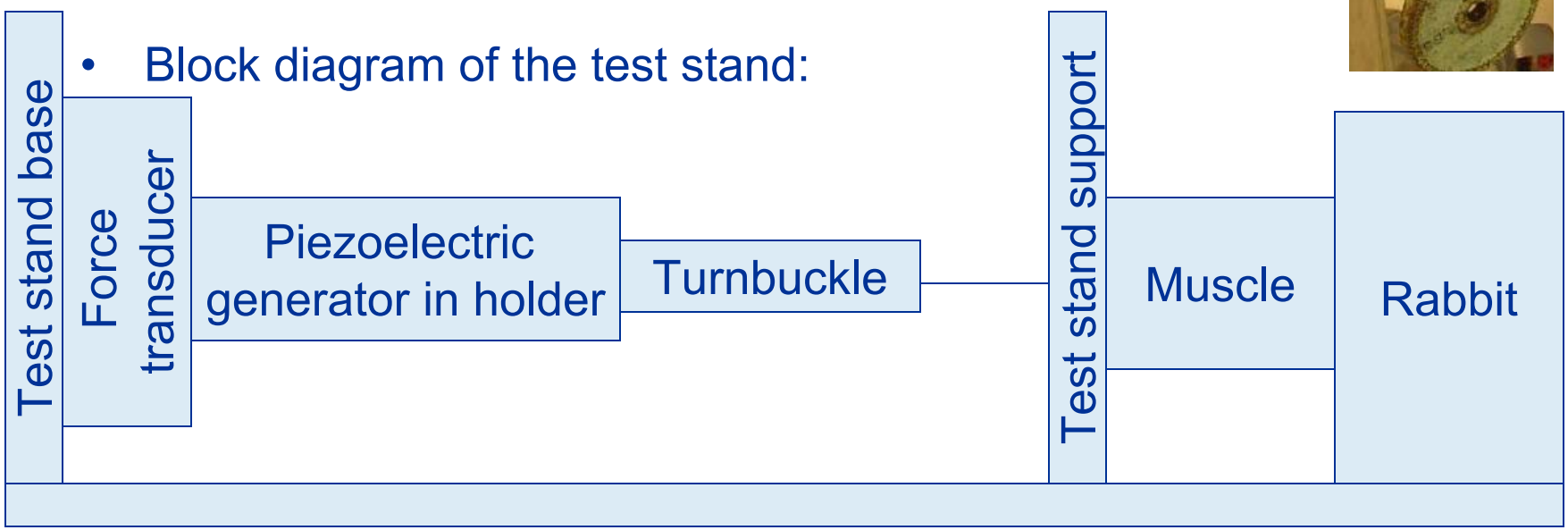


ANIMAL TEST PREPARATIONS

- The rabbit quadriceps is being used as the animal muscle model
  - The twitch force has been verified to be between 30 and 50 N.

- The test stand and connection to tendon can withstand:
  - 15 lbs (67 N) of static weight
  - Dynamic forces consisting of peak forces of 60 N

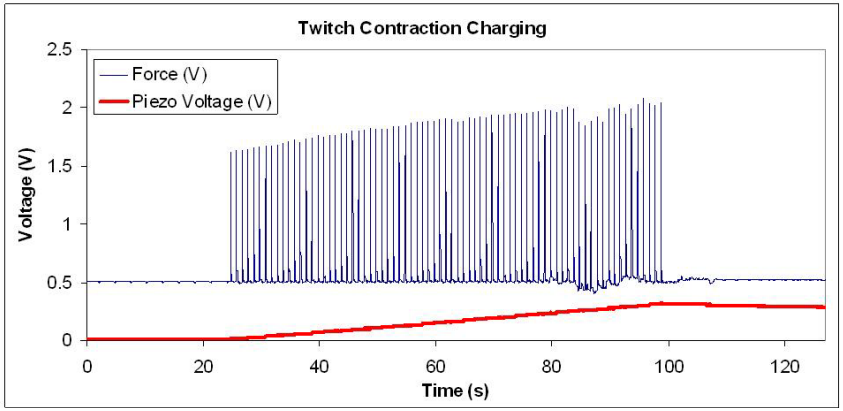
- Block diagram of the test stand:



ANIMAL TEST PROTOCOL

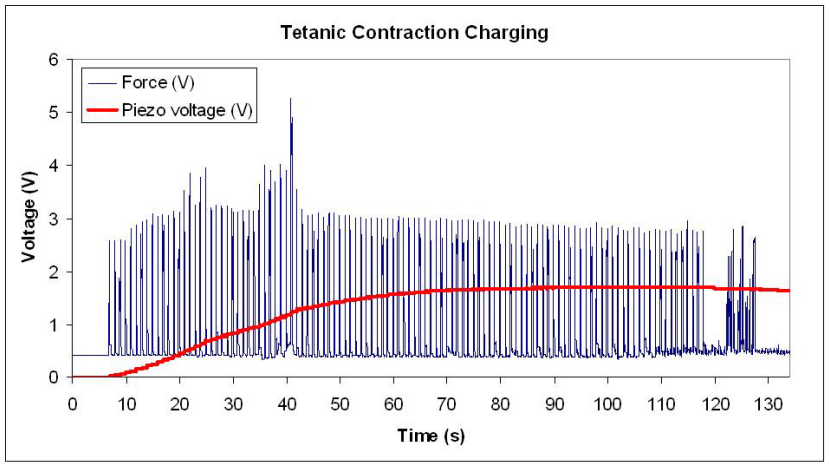
- Set up test stand
  - Force transducer
  - Piezoelectric generator in holder, a Lead Magnesium Niobate stack generator was used (TRS Ceramics, PMN 32%PT Actuator)
  - Connect the piezoelectric generator to the storage circuit
- Perform surgery
  - Expose patellar tendon, disconnect from tibia, drill hole through patella, pull wire through hole and crimp
  - Expose the femoral nerve and place a cuff electrode around the nerve
- Connect rabbit to test stand
  - Connect wire between patella and turnbuckle/generator/force transducer
  - Use tie wrap to connect the tibia/femur to the test stand
- Find stimulation parameters
  - Adjust the muscle length to that which produces maximum force
  - Find the threshold current for producing maximum twitch force
- Run Experiment
  - Stimulate femoral nerve
  - Record the voltage across the load resistor

ANIMAL TEST RESULTS



Twitch Contractions

Average peak force = 32 N
Voltage gain = 0.3 V
Output power = 30 nW
Charging time = 74 sec



Tetanic Contractions

Average peak force = 60 N
Voltage gain = 1.7 V
Output power = 1 μW
Charging time = 85 sec

The prototype generator system was charged with a physiological muscle

IMPROVEMENTS/FUTURE WORK

- Current output power levels are below predicted values. Improvements that can be made to improve output power.
  - Need to ensure piezoelectric generator is square with holder and force is only applied in direction normal to the cross sectional area of the generator.
  - Use low power diodes in an effort to increase output power levels.
  - Explore stimulation parameters to maximize output power. A trade-off exists between input stimulation power and output force produced by the muscle.

- The input power necessary for the motor nerve stimulations was greater than the output power during the first animal experiment.
  - A size correction and improvement in electrode placement will reduce the amount of stimulation input power needed.

- Use a low powered stimulator and circuitry to demonstrate self-sustaining stimulated muscle contractions and power generation.

ACKNOWLEDGEMENTS

- Committee:
  - Dr. Ken Gustafson, CWRU BME Department
  - Dr. Kevin Kilgore, CWRU BME Department
  - Dr. Steve Garverick, CWRU EECS Department
  - Dr. Bob Kirsch, CWRU BME Department
  - Dr. Dustin Tyler, CWRU BME Department

- In addition:
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  - Ms. Katie Hallahan, CWRU Student
  - Mr. Alex Frayna, CWRU Student
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QUESTIONS AND COMMENTS?