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PRINCIPAL INVESTIGATOR: Mark Pitkin

RECIPIENT: Poly-Orth International
Sharon MA 02067-1518

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Mark Pitkin

mpitkin@tuftsmedicalcenter.org

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14. ABSTRACT
The investigators wish the American Veterans and civilians with amputations can use powered prostheses with direct skeletal attachment and direct bidirectional neural control. Since 2004, their work has been devoted improving a skin-device and bone-device interface. Current research is designed as a translational study to develop Skin and Bone Integrated Pylon with Peripheral Neural Interface (SBIP-PNI) directly attached to the residuum and the powered prosthetic hand with bidirectional control. .

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None provided

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1. **INTRODUCTION:** Narrative that briefly (one paragraph) describes the subject, purpose and scope of the research.

The investigators wish the American Veterans and civilians with amputations can use powered prostheses with direct skeletal attachment and direct bidirectional neural control. Since 2004, their work has been devoted improving a skin-device and bone-device interface. Current research is designed as a translational study to develop Skin and Bone Integrated Pylon with Peripheral Neural Interface (SBIP-PNI) directly attached to the residuum and the powered prosthetic hand with bidirectional control.

2. **KEYWORDS:** Provide a brief list of keywords (limit to 20 words).

Direct skeletal attachment; powered prosthesis; neural interface; bidirectional control system.

3. **ACCOMPLISHMENTS:**
What were the major goals of the project?

Goals/Milestones

Year 1
 Manufacture the integrated pylons with peripheral neural interface (SBIP-PNI) for animal studies and fabricate the powered prostheses with sensory feedback
Milestones #1: Meeting the Poly-Orth specification and passing the QC tests – planned in Q2; current completion 100%
Milestone #2: Ship the implants to the Pine Acre Rabbitry/Farm (PARF) and to Georgia Institute of Technology (GIT – – planned in Q2; current completion 100%.
Comment: the site #2 for animal studies with pigs has been changed from PARF to DaVinci Biomedical Research, Lancaster, MA, with corresponding approval.
 Implant SBIP-PNI into cats - planned in Q4; current completion 50%
 Supply cats with powered prostheses with sensory feedback and initiate gait study- planned in Q4: will be provided in Q1 and Q2 of Year 2

Year 2
 Conclude cat gait study with and without sensory feedback -planned in Q5
 Implant SBIP-PNI into Yorkshire Swine and conduct gait study with and without sensory feedback

Year 3
 Perform mechanical testing of device skin and device-bone attachment Perform histological analysis of the samples
 Conclude pig gait study with and without sensory feedback
 Demonstrate infection free sustainable device-body interface with the SBIP-PNI
 Demonstrate that adverse events rate (AER) in animal study is lower than the established threshold
 Submit application for IDE to the FDA Comments/Challenges/Issues/Concerns

What opportunities for training and professional development has the project provided?
If the project was not intended to provide training and professional development opportunities or there is nothing significant to report during this reporting period, state "Nothing to Report."

Nothing to Report

How were the results disseminated to communities of interest?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Abstracts and Publications

Park H, Islam MS, Grover MA, DeWeerth SP, Prilutsky BI. Closed-loop control of a transtibial prosthesis with active ankle joint and sensory feedback. In: Annual Meeting of Society for Neuroscience. Washington, DC, November 11-15, 2017.

A prototype of a neural, powered transtibial prosthesis for the cat. Park H, Islam MS, Grover MA, Klishko AN, Prilutsky BI, DeWeerth SP. Frontiers in Human Neuroscience (in preparation).

What do you plan to do during the next reporting period to accomplish the goals?
If this is the final report, state "Nothing to Report."

Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

In Year 2 and 3, we plan

- to complete the study in cats with powered prostheses attached to the residuum via Skin and Bone Integrated Pylon with Peripheral Neural Interface (SBIP-PNI) to demonstrate effectiveness of the neural control in animal gait compared to passive prostheses.
- To complete the study in pigs with the SBIP-PNI to demonstrate safe and sustainable bone-device and skin-device interface.

4. IMPACT: Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project relative to:

What was the impact on the development of the principal discipline(s) of the project?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that an intelligent lay audience can understand (Scientific American style).

1. Cat study at the Georgia Institute of Technology

From October 2016 to June 2017, the Georgia Tech group has developed a prototype of a

powered, sensing transtibial prosthesis for cats. The prosthesis development has included (i) selection of appropriate components (motor, buttery, electronics, stimulator, etc.) that satisfy constraints on the mass of the cat distal leg and ankle power production; (ii) designing electronics, control algorithms, carbon fiber feet and a system for attaching the prosthesis to the percutaneous pylon; (iii) manufacturing parts and integrating them together and (iv) testing (see below).

1.1 Prototype of powered, sensing transtibial prosthesis for cats

The Georgia Tech group has developed a prototype of sensing, bone-anchored transtibial prostheses for the cat and a closed-loop control system to govern the powered prosthetic ankle joint. This prosthesis should provide tactile sensation of ground contact by the prosthesis and control of the prosthetic ankle using recorded activity from the residual muscles.

Figure 1 illustrates a detailed system block diagram of the electronics of the powered sensing transtibial prosthesis. Electronics inside the prosthesis consisted of five functional blocks: (1) Microprocessor unit (MCU), (2) Force-position sensor, (3) Motor, (4) Battery and coil, and (5) Power management. The model of the MCU (CC2510F32 MCU, Texas instruments, TX, USA) was selected for its versatile functionalities with low-power consumption. It has several built-in functional blocks such as the 8051 microprocessor, 8-channel, 12-bit analog-to-digital converters, a UART interface, and a 2.4 GHz ISM band wireless transceiver.

To detect contact of the prosthetic foot with the ground, the ThinPot linear position-force sensor (Spectra symbol, UT, USA) was selected. It was fixed on the bottom of the J-shape foot, between the J-shape plastic foot and the rubber layer. Although a linear position sensor cannot measure normal force with high resolution, the 1-bit resolution of the pressure magnitude was sufficient to detect paw contact during walking in cats (Park et al. 2015, 2016, 2017). In addition, the position sensor provided the anterior-posterior contact position that was used to adjust the prosthetic joint angle position during the contact with the ground.

To actuate the ankle joint, we selected a linear motor (PQ12-63-06-P, Firgelli, BC, Canada) instead of a conventional rotary motor, because linear motors can pull and push, a single motor could work as an ankle extensor (like the soleus muscle, SO) and an ankle flexor (like the tibialis anterior muscle, TA). For the same reason, human powered transtibial prostheses and orthoses have employed linear motors (Realmuto et al. 2015; Garcia et al. 2011; Blaya et al. 2004). Because An H-bridge motor driver (DRV8837, Texas instruments, TX, USA) was used to generate a voltage output with switching polarity.

A Li-polymer rechargeable battery (400 mAh) was mounted on one side of the linear motor (Fig. 3A). It could generate current of up to 800 mA, which exceeded the current required to power the linear motor PQ12-63-06-P (i.e., 550 mA). Considering that the linear motor could consume ~200 mA to generate force of 20 N, which was higher than the target GRF peak (~15 N, Fig. 5) and that the other electronic components consumed less than 20 mA in total, the battery would last more than 2 hours, given the mean duration of the extension (stance) phase during cat walking with self-selected speed (Prilutsky et al., 2005; Prilutsky et al., 2011; Markin et al., 2012). The inductive coil for wireless recharging was placed at the proximal end of the J-shape foot (Fig. 2A). A power management consisted of a low-dropout voltage regulator, a step-up DC-DC converter (LM2621, Texas instruments), and a battery charging IC(LTC4054, Linear Technology, AZ, USA).

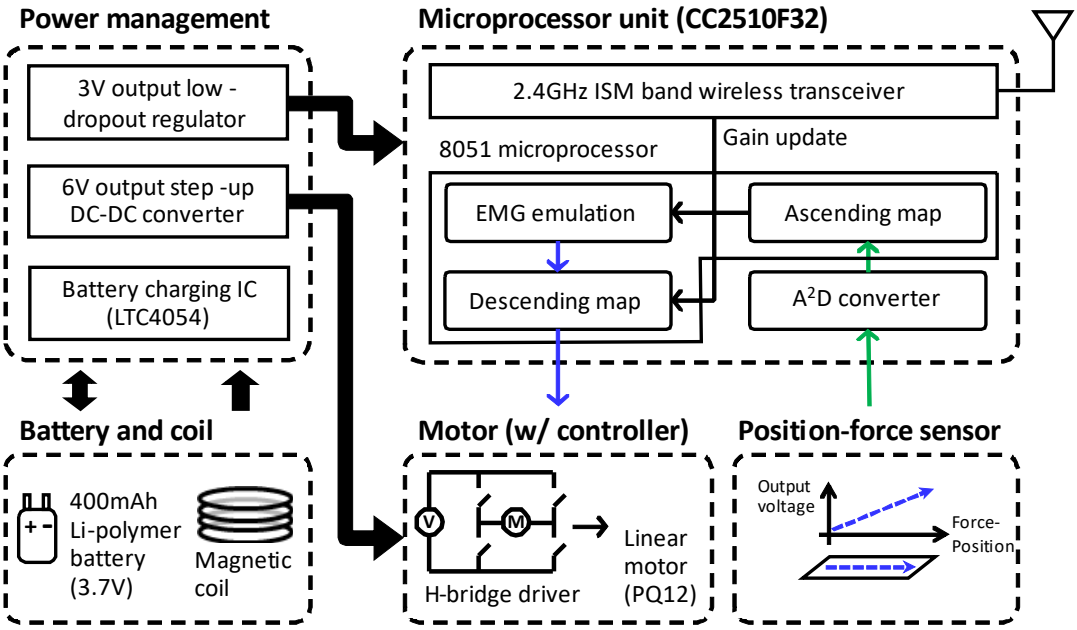

Figure 1. Detailed system block diagram of the powered sensing transtibial prosthesis. Ascending pathway for feedback signals is depicted by green arrows; descending pathway for feedforward control signals id depicted by blue arrows. For other details, see text.

A 3V-output was used to provide supply for MCU and sensor, 6V-output was used for the linear motor, and LTC4054 controlled the charging current of the Li-polymer battery.

An MCU CC2510F32 was used to control the wireless communications with the MCU on the prosthesis. A force sensing resistor FSR406 (Interlink electronics, CA, USA) measured ground reaction force exerted by the prosthesis, while a computer monitored the measured ground reaction force in real time and changed the ankle extension gain β_{SO} (see eq. 1 below) by a predefined step magnitude to adjust the peak ground reaction force to the target value. The MCU generated a pulse-width modulated (PWM) output to change the gain β_{SO}. Based on the operating principle of the DC motor, we assumed that gain β_{SO} was proportional to the duty factor of PWM control signal (Weber et al. 1965). A user set the target gait metric on the computer screen with a LabView (National Instrument, TX, USA) application and β_{SO} was updated every cycle of the gait.

Figure 2A demonstrates the actual implementation of the powered sensing transtibial prosthesis. A rectangular aluminum rod served as a main frame of the prosthesis and connected the J-shaped foot and electronic components with the percutaneous pylon that would be implanted into the medullary cavity of the cat tibia and interfaced with residual cutaneous nerves and SO and TA muscles via implanted electrodes. A J-shape foot was 3D-printed using ABS plastic. It had thickness of 3 mm, which was sufficient to withstand ground reaction forces produced by the cat hindlimb during walking (see below). A finger-sized linear motor (see above) with a 10-mm lever arm was attached on a side of the aluminum rod. Two separate printed circuit boards (PCBs) were placed to the right of the linear motor on the flat part of the J-shaped foot. The MCU and power management integrated with the PCB were placed on a side of the linear motor. The motor driver and sensor interface integrated with the PCB were fixed on the flat part of J-shaped foot. Finally, a Li-polymer battery was mounted on the left side of the linear motor.

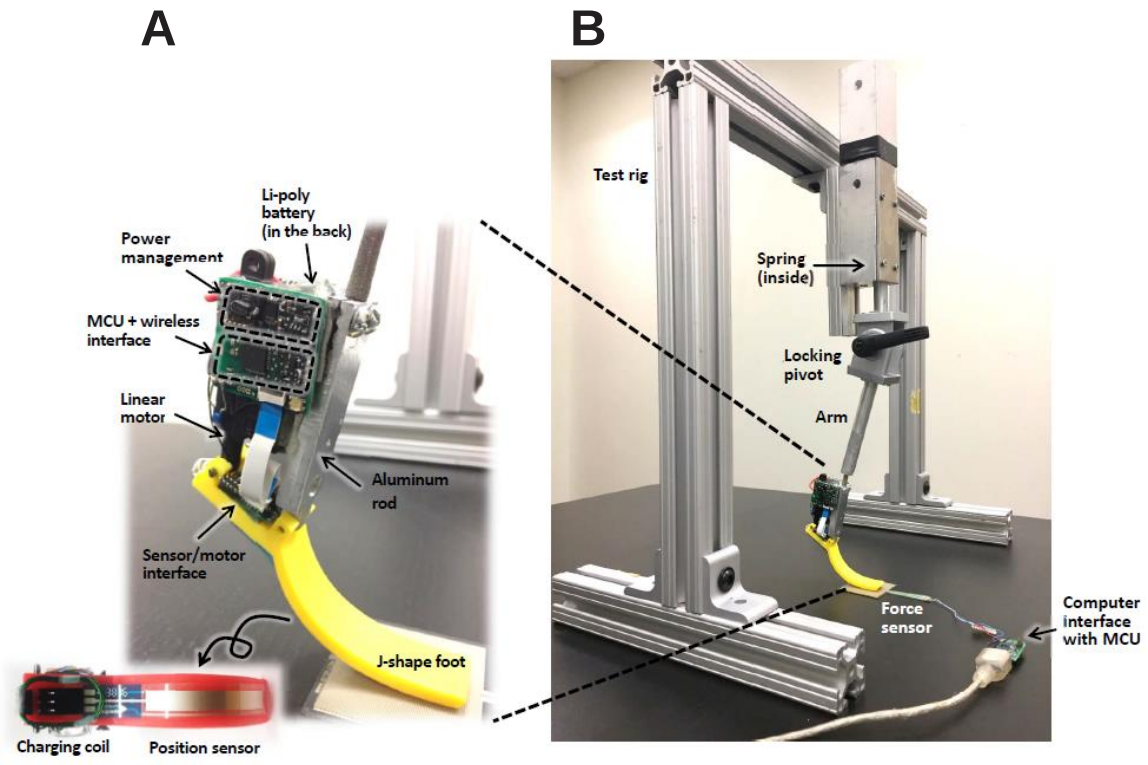

Figure 2. A: Prosthesis prototype. B: Test rig with the attached prosthesis.

Every component of the prosthesis was selected to meet the size, mass and power output parameters of the cat foot with distal tibia and the ankle joint. The average length of the cat shank is approximately 110 mm for cats with body mass of 3 to 4 kg (Prilutsky et al., 2011; Farrell et al., 2014; Klishko et al., 2014). The maximum mass of the prosthesis was set at 80 g, considering that the average mass of the cat hind digits, tarsals and half of the shank for a 3.5-kg cat is 78 g (see Table 1 in Hoy and Zernicke 1985). The average peak of the ankle moment during level and 27-deg upslope walking is 0.73 – 0.75 Nm and 1.09 – 1.27 Nm, respectively (Gregor et al., 2006; Prilutsky et al., 2011). The average peak of ankle positive power in the same conditions is 0.86 W and 1.82 W, respectively (Prilutsky et al., 2011).

The cat transtibial prosthesis was designed based on the above information. The length of the aluminum rod was set at a half of the shank length, i.e. 55 mm. The linear motor PQ12-63-06-P, Li-polymer battery and other prosthetic components were selected to meet the requirements for the maximum prosthesis mass and moment generation ability. As a result, the prosthesis mass was 80 g and the maximum measured moment during the testing (see below) was 0.6 Nm, which is close to the maximum ankle moment during level walking in the cat.

We tested the developed prosthesis and control algorithms in a test rig that held the prosthesis slightly above the ground (Fig. 3B). Previously recorded EMG activity of an ankle extensor SO and a flexor TA and experimentally obtained ankle joint moments during walking in intact cats (Fig. 4) were used to establish the EMG-joint moment regression equation that would be implemented in the control of the prosthetic motor during prosthetic walking in the cat. The equation had the following form:

$$M_{pANK}(t) = \beta_0 + \beta_{SO} EMG_{SO}(t + \Delta t) + \beta_{TA} EMG_{TA}(t + \Delta t), \quad (1)$$

where M_{pANK} is the ankle joint moment predicted from recorded EMG activities of SO and TA muscles, i.e. $EMG_{SO}(t+\Delta t)$ and $EMG_{TA}(t+\Delta t)$, respectively; t is time and Δt is the electromechanical delay between the appearance of EMG activity and the onset of the resultant joint moment; $\beta_0 = 0.080020$, $\beta_{SO} = 0.890853$ and $\beta_{TA} = -0.129422$ are empirical constants. The above constants were derived from the previously obtained ankle resultant moments (Fig. 3C) and the corresponding low-pass filtered EMG activities (Butterworth 4th order filter, cut-off frequency 6 Hz) of SO (Fig. 3A) and TA (Fig. 3B) using software STATISTICA 7 (StatSoft, USA). Approximately two-thirds of total 22 walking cycles (n=15) from 3 cats were randomly selected and used to derive the regression equation (1). The remaining cycles (n=7) were used to compare the predicted ankle moment M_{pANK} with the experimental one (Fig. 3D). The coefficient of multiple correlation for eq. 1 was *r* = 0.836. The detailed description of how the joint moments and EMG activities were obtained and processed has been described in the original publications (Prilutsky et al., 2005; Prilutsky et al., 2011; Markin et al., 2012). Briefly, the resultant ankle moment was computed based on motion capture of hindlimb kinematics, recorded ground reaction forces and estimated inertial parameters of the hindlimb segments. EMG activity of SO and TA muscles was simultaneously recorded via chronically implanted muscle electrodes. Recorded EMG signals were full-wave rectified and low-pass filtered. The EMG magnitude was normalized to the peak of the low-filtered EMG signal across all recorded walking cycles within each cat. The joint moments, ground reaction forces and low-pass filtered EMGs were time normalized to the duration of the walking cycle. The descending map (i.e. the EMG-ankle moment relationship, eq. 1) was simplified for testing the prosthesis in the test rig. EMG activity of SO and TA muscles was modeled as a unit step function to represent the timing of EMG activity. Specifically, EMG_{SO} was computed as

$$EMG_{SO}(t) = H(t - \Delta t_{SO}) - H(t - (\Delta t_{SO} + T_{SO})), \quad (2)$$

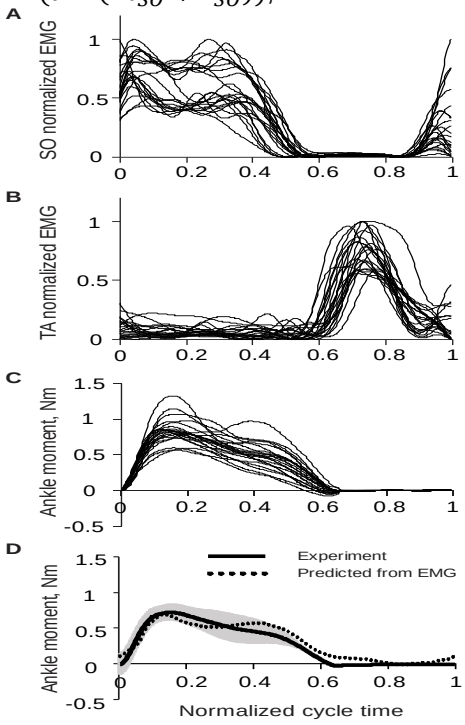

Figure 3. Ankle joint moment and EMG activity of soleus (SO) and tibialis anterior (TA) muscles during level walking in the cat.

where Δt_{TA} is a phase delay between the previous stance phase offset and subsequent TA EMG onset, T_{TA} is the duration of EMG_{TA} activity; Δt_{TA}= 400 ms and T_{TA} = 200 ms (Prilutsky et al., 2005; Prilutsky et al., 2011; Markin et al., 2012).

The simulated EMG signals (eq. 2 and 3) were used to control the linear motor with a dual polarity. The reason for choosing a dual polarity motor was to replicate both ankle extension and ankle flexion muscle actions. The ankle joint moment was calculated using eq. 2 and simulated EMG activity patterns of SO and TA obtained from eq. 2 and 3. Because EMG signals had a unit magnitude, relative magnitude difference between SO EMG and TA EMG could be represented by the motor gain for extension (β_{SO}) and flexion (β_{TA}) action, assuming β_0 = 0. The neuromechanical delay Δt for SO and TA in eq. 1 was assumed the same. Equation 1 for computing ankle moment was not applicable for co-activation of SO and TA. The SO-TA co-activation was implemented in the prosthesis as a "brake" and corresponded to cessation of the linear motor displacement.

The prosthesis was mounted on the test rig via a zinc-plated compression spring (Fig. 2B). The stiffness coefficient of the compression spring was 0.36 N/mm that allowed for vertical displacements of 40-47 mm when forces of 14-17 N were applied to the prosthesis. Right before the test, the prosthesis was supported by the experimenter hand above the ground such that the compression spring was fully compressed. When the hand released the prosthesis, it touched the ground; the position sensor detected the ground contact and the touch-feedback signal initiated an ankle extension moment ($M_{pANK} > 0$ see eq. 2 and 3). When full extension of the ankle joint was reached, the contact with the ground was lost due to take off of the prosthesis, a flexion ankle moment was generated ($M_{pANK} < 0$ see eq. 2 and 4) and the prosthesis returned to the initial position above the ground completing the cycle. Each cycle was initiated with the help of the experimenter's hand multiple times.

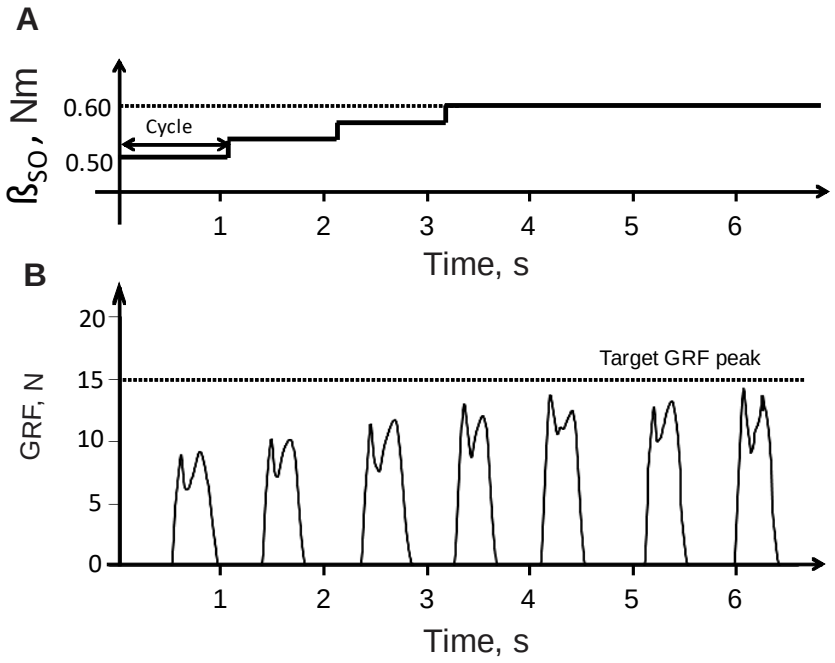

Figure 4. Vertical ground reaction force (GRF) recorded during level walking in the cat (solid line and shade, mean±SD; Prilutsky et al. 2011) and mean GRF r last 3 cycles of testing the prosthesis (dashed line).

The initial value of the ankle extensor gain β_{SO} was set at 0.5 Nm and the step magnitude, at 0.033 Nm. Because the measured peak ground reaction force (GRF) was smaller than the target GRF peak of 15 N, the feedback controller increased gain β_{SO} by 0.033 Nm for every cycle in which the recorded GRF was lower than 15 N. After three cycles, β_{SO} values saturated to 0.6 Nm as the maximum gain of the selected linear motor (Fig. 4A). The GRF peak increased with the increasing β_{SO} until the gain saturated in cycle 4 (Fig. 4B).

Time profiles of GRF measured under the prosthetic foot in 7 consecutive cycles had a two-peak pattern (Fig. 4B). Peak values increased from ~9 N in cycle 1 to ~14 N in cycles 5 – 7. The comparison of the prosthetic GRF averaged across cycles 5 through 7 with the experimental GRF recorded previously during level walking in cats (Gregor et al., 2006; Prilutsky et al., 2011) demonstrated close qualitative and quantitative agreements (Fig. 5). Specifically, both patterns had two peaks – one in early stance and the other one in late stance. The mean peak GRF generated by the prosthesis (13.6 N) was within one standard deviation of the experimental GRF mean peak (14.9±1.6 N).

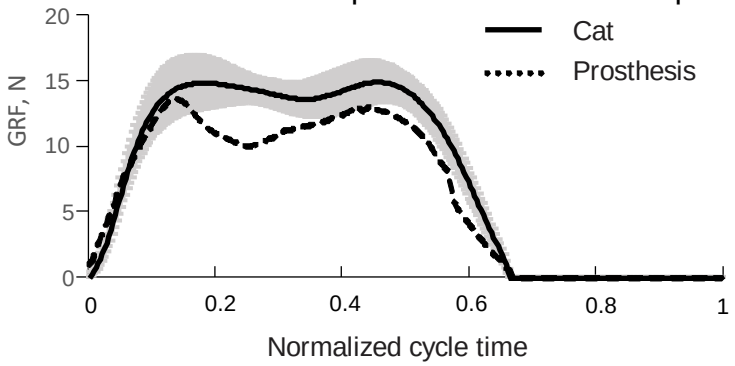

Figure 5. Vertical ground reaction force (GRF) recorded during level walking in the cat (solid line and shade, mean±SD; Prilutsky et al. 2011) and mean GRF recorded during the last 3 cycles of testing the prosthesis (dashed line).S

1.2 Implantation of SBIP-PNI pylon and nerve cuff and EMG electrodes

After animal training and baseline walking data collection were completed, 4 cats were implanted with the SBIP-PNI pylons in the distal-mid tibia. The surgical procedures were identical to those in our previous study (Farrell et al. 2014) and performed in sterile conditions under isoflurane anesthesia. In addition, nerve cuff electrodes were implanted on the distal tibial and sciatic nerves and in the proximal parts of SO and TA muscles. The leads from the electrodes were passed through the tibial marrow cavity and the central channel in the pylon. After closing skin, the leads were secured in silicon, and the residual limb with the implant casted as described previously (Farrell et al. 2014).

After surgery the animals received pain medication and antibiotics. Blood samples were taken to monitor systemic infection. X-rays were taken prior to and 2 weeks after the surgery. The x-ray images demonstrated generally successful surgeries (Fig. 7).

Starting from week 6 after the surgery, we plan to load the implant to promote bone-implant integration. At 10 weeks, we will remove the cast and attached the prosthesis.

In the meantime, we will train the other group of 4 cats to walk on the walkway and split-belt treadmill.

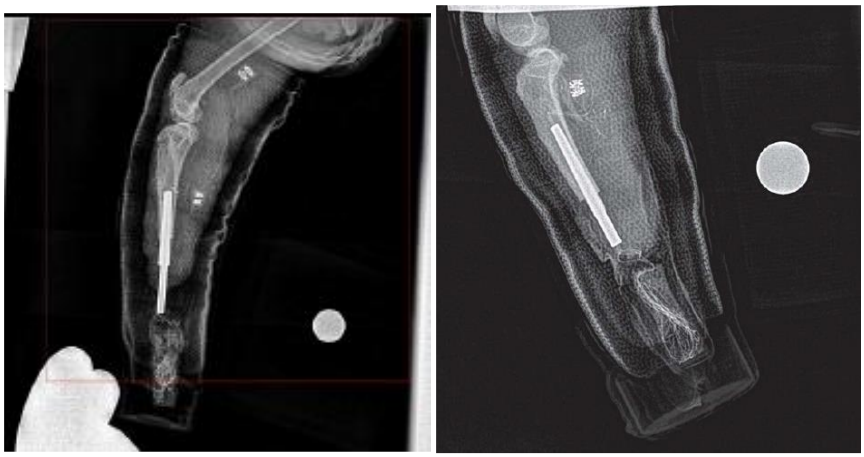

Figure 6. X-rays of cats QM10 and QM11 taken 2 weeks after implantation the SBIP-PNI pylon and nerve and muscle electrodes.

2. Pig study at DaVinci Biomedical

2.1 Preparations for Year 2 study with pigs

- New molds were fabricated for manufacturing the SBIP-PNI pylons for pigs.
- New SBIP-PNI pylons were manufactured and HIP processed.
- Corresponding new reamers for the surgical implantation have been fabricated.
- Strideway System for gait analysis (Tekscan, Inc) has been obtained, assembled at the DaVinci facility. Training was conducted by Tekscan representatives.
- Pilot study with two pigs at the DaVinci Research Biomedical, Lancaster, MA has been conducted in Q3-Q4. The study was designed for evaluating the implantation technique in pigs and skin interface for the new SBIP-PNI pylons with consequent analysis of acceptance of the prosthetic gait by the animal by analysis of the symmetry rate of loading on the involved and uninvolved legs (Table 1).

Table 1. DB-516 Animal Pilot 2 study data

DB-516 Pilot 2

Animal Number / Sex	Receipt Date	Acclimation Release	Acclimation Days
55-023F	7/26/2017	8/1/2017	6

Procedure Date	Day	Body Condition score	Comments / Notes	SX Clinical Pathology (CBC, CRP, Serum)	Body Weight (Kg)	Bupivicaine 5 mg/mL (mL)	Cefazolin (mg @ hh:mm)	Buprenorphine 0,3 mg/mL (ml)	Carprofen / Rimadyl 50 mg/ml (ml)	Excede 200 mg/ml (ml)	Doxapram 20 mg/mL (mL)	Bacitracin 50,000 U/mL (mL)	Baytril/Enrofloxacin 100 mg/ml (ml)	Bandage Change (Y/N)	Walking pain (Y/N)	Healing (Y/N)	Inflammation (Y/N)	Abnormalities (Y/N)	Repairs intervention (Y/N)
8/2/17	0	5/9	Surgery to implant device 75 mg/hr Fentanyl patch applied at 0615. Procedure start time 0714. Mark the incision outline - first incision , disarticulated tibia from metatarsals - also removed distal aspect of the fibula. Drilled medullary cavity, followed by reamer. Bacitracin 9.8 mL irrigated into amputation site prior to implant placement at 0900. Placed device into distal end of tibia. Whet into medullary cavity. Placed skin flap over post. Fluoroscopy post-op. Placed aluminum prosthetic support. Recovered animal.	CBC, CRP, Serum chem	39.2	5.0	4.0 @ 0715	1.3	1.6	1.0	0.5	9.8							
8/2/17	0	5/9	Sedation for bandage change/repair at ~1400. Cleaned incision/implant site. replacement		39.2														
8/7/17	5	5/9	Incision healing well/normal. Inflammation: incisional and around implant. No odor present. Granulation tissue around implant. Cleaned implant with betadine. Rewrapped with roll cotton and Elastikon. Placed aluminum support over implant and distal tissue -wrapped with Elastikon sutured to skin.		37.6			1.5		1.0				Y	Y	Y	Y	Y	bandage change/repair at ~1400.
8/15/17	13	3/9	Granulation tissue around implant. Sutures removed. Slight odor, dehiscence of anterior aspect near implant. No attachment to implant. Excede and Baytril given IM at 10:33. Culture taken of implant/SC interface. Fluoroscopy performed. Rebandaged.	CBC, CRP, Serum chem	38.5					1.0			3.0	Y	Y	Y	Y	Y	bandage change/repair at ~1000.
8/23/17	21	5/9	Tissue at implant transition area is granulated and healing. Mild inflammation. Normal bandage change. No abnormalities, tissue is contracting around implant.		42.5				1.7	1.0			3.0	Y	Y	Y	Y	N	bandage change/repair at ~1100.
8/30/17	28	4/9	Bandage change, healing: granulation tissue at implant site moderate. Inflammation: irritation aof posterior stiffle due to pressure of cup against leg. Repairs / Inteventions: recovered implant site post removal of scabs at distal aspect. Abnormalsities: none	CBC, CRP, Serum chem	43.5					1.0			3.0	Y	Y	Y	Y	N	bandage change/repair at ~0945.

- Pre-surgery gait analysis was conducted with the animals #1 and 2.
- Symmetry rate for loading on the right and left hind limbs was calculated for further comparison with post-surgery gait on prosthesis.
- Implantation of the SBIP pylons (Fig. 7) was performed.

2.2 Development and Fabrication of the Skin and Bone Implanted Pylons with peripheral nerve interface (SBIP-PNI)

For direct skeletal attachment (DSA) of the powered prostheses, the Skin and Bone Implanted Pylons with peripheral nerve interface (SBIP-PNI) were developed and fabricated by the Poly-Orth International.

The SBIP-PNI is capable of transmitting pressure information from the surface of prosthesis to the user via electrical stimulations of sensory nerves thus providing tactile sensations. The first breakthrough study in direct transmission of the neuromuscular signal from inside the residuum to an outside device via direct skeletal attachment was conducted by the applicants. The transmission was made possible by the developed SBIP for peripheral nerve interface (SBIP-PNI). A neuromuscular signal was subsequently recorded in an acute animal experiment via the developed system (Pitkin, Cassidy et al. 2012).

The same SBIP-PNI interface can also deliver feedforward control signals recorded from residual muscles and muscle nerves to the prosthetic motors.

Fig. 8, A depicts the conical titanium cores of the SBIP-PNIs, which are to be positioned in the mold (Fig. 8, B). Canals of 1 mm in diameters for passing the wires between the muscles/nerves and the prosthesis' motor were fabricated by Ramco Machine, LLC, Rowley, MA, After the spaces between the cores and the mold walls are filled with the titanium particles of selected grade, the mold is positioned in the fence for sintering following the previously developed specification (Pitkin, Raykhtsaum et al. 2009).

Figure 7. a - Reamer for preparing the bone marrow canal for implanting the SBIP; b - SBIP matching the shape of the pig's tibia bone.

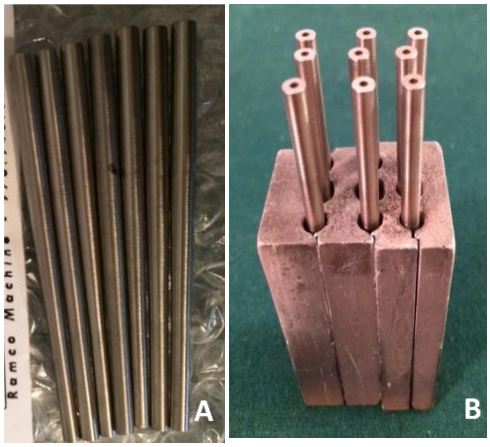

Figure 8. A - conical cores with central canal for sintering the SBIP-PNIs; B - the cores in the mold before sintering.

References
Farrell, B., B. Prilutsky, R. Kistenberg, J. Dalton, A. Strong and M. Pitkin (2014). "An animal model to study skin-implant-bone integration and prosthetic gait with limb prostheses directly attached to the residual limb." Clinical Biomechanics **29** 336–349: [PMCID: PMC3959271] http://www.ncbi.nlm.nih.gov/pubmed/24405567
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Prilutsky, B. I., H. Maas, M. Bulgakova, E. F. Hodson-Tole and R. J. Gregor (2011). "Short-term motor compensations to denervation of feline soleus and lateral gastrocnemius result in preservation of ankle mechanical output during locomotion." Cells Tissues Organs **193**(5): 310-324.
Prilutsky, B. I., M. G. Sirota, R. J. Gregor and I. N. Beloozerova (2005). "Quantification of motor cortex activity and full-body biomechanics during unconstrained locomotion." J Neurophysiol **94**(4): 2959-2969. [PMID: 15888524]. http://www.ncbi.nlm.nih.gov/pubmed/15888524.

What was the impact on technology transfer?

If there is nothing significant to report during this reporting period, state "Nothing to Report." Describe ways in which the project made an impact, or is likely to make an impact, on commercial technology or public use, including:

- *transfer of results to entities in government or industry;*
- *instances where the research has led to the initiation of a start-up company; or*
- *adoption of new practices.*

Nothing to report for Year I
Recommendations for implantation of the pylons with peripheral neural interface and on bidirectional control of powered prostheses are anticipated at the completion of the project.

What was the impact on society beyond science and technology?

If there is nothing significant to report during this reporting period, state "Nothing to Report." Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as:

- *improving public knowledge, attitudes, skills, and abilities;*
- *changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or*
- *improving social, economic, civic, or environmental conditions.*

The investigators wish the American Veterans and civilians with amputations can use powered prostheses with direct skeletal attachment and direct bidirectional neural control, which could improve the quality of life and social integration of the patients.

5. **CHANGES/PROBLEMS:** The Project Director/Principal Investigator (PD/PI) is reminded that the recipient organization is required to obtain prior written approval from the awarding agency Grants Officer whenever there are significant changes in the project or its direction. If not previously reported in writing, provide the following additional information or state, "Nothing to Report," if applicable:

Nothing to report

Changes in approach and reasons for change

Describe any changes in approach during the reporting period and reasons for these changes. Remember that significant changes in objectives and scope require prior approval of the agency.

Nothing to report

Actual or anticipated problems or delays and actions or plans to resolve them

Describe problems or delays encountered during the reporting period and actions or plans to resolve them.

1. Cat study

In the beginning of the project in October 2016, the Georgia Tech group ordered 8 cats from the animal supplier. At that time the available cats were too young to start the study, therefore their arrival was postponed for 7 months. Since receiving animals in late May 2017, the Georgia Tech group trained 4 cats to walk on a walkway and split-belt treadmill, and recorded baseline full-body mechanics of locomotion of these cats prior to implantation surgery. Currently, the surgeries were conducted on 4 cats. The other 4 cats will be taken for surgery in Q1 of Year 2.

2. Pig study

In the pilot study in the pig #1 at DaVinci, the soft tissues around the outside portion of the SBIP pylon showed swelling two weeks after implantation. That caused movement of the tissues envelope in a direction along the longitudinal axis of the pylon. Debridement of the residuum's distal portion was performed to improve the healing, but the following untreatable infection caused termination of Pilot 1study.

Modifications in preparation of the skin flap has been tested in a cadaver study. These modifications were implemented in the next Pilot 2 study (approved by ACURO) with positive preliminary results. We are currently following the pig #2 with blood testing, x-ray, and behavioral observations. We plan to continue the follow-ups in Q1 of Year 2 (Table 1).

To address the possible tissues swelling after implantation procedure, we plan to modify in Year II the SBIP-PNIs by extending the porous cladding zone in the skin-device interface by 20mm.

Changes that had a significant impact on expenditures
Describe changes during the reporting period that may have had a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.

Nothing to Report

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents
Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, biohazards, and/or select agents during the reporting period. If required, were these changes approved by the applicable institution committee (or equivalent) and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.

Significant changes in use or care of human subjects

N/A

Significant changes in use or care of vertebrate animals.

Pilot 2 study with one pig has been approved by ACURO.

Significant changes in use of biohazards and/or select agents

N/A

6. PRODUCTS: List any products resulting from the project during the reporting period. If there is nothing to report under a particular item, state "Nothing to Report."

- **Publications, conference papers, and presentations**
  Report only the major publication(s) resulting from the work under this award.

  Journal publications. *List peer-reviewed articles or papers appearing in scientific, technical, or professional journals. Identify for each publication: Author(s); title;*

journal; volume: year; page numbers; status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).

A prototype of a neural, powered transtibial prosthesis for the cat. Park H, Islam MS, Grover MA, Klishko AN, Prilutsky BI, DeWeerth SP. Frontiers in Human Neuroscience (in preparation).

Books or other non-periodical, one-time publications. *Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like. Identify for each one-time publication: Author(s); title; editor; title of collection, if applicable; bibliographic information; year; type of publication (e.g., book, thesis or dissertation); status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).*

Nothing to report

Other publications, conference papers, and presentations. *Identify any other publications, conference papers and/or presentations not reported above. Specify the status of the publication as noted above. List presentations made during the last year (international, national, local societies, military meetings, etc.). Use an asterisk (*) if presentation produced a manuscript.*

Park H, Islam MS, Grover MA, DeWeerth SP, Prilutsky BI. Closed-loop control of a transtibial prosthesis with active ankle joint and sensory feedback. In: Annual Meeting of Society for Neuroscience. Washington, DC, November 11-15, 2017.

- **Website(s) or other Internet site(s)**

List the URL for any Internet site(s) that disseminates the results of the research activities. A short description of each site should be provided. It is not necessary to include the publications already specified above in this section.

Nothing to report

- **Technologies or techniques**

Identify technologies or techniques that resulted from the research activities. In addition to a description of the technologies or techniques, describe how they will be shared.

Nothing to report

- **Inventions, patent applications, and/or licenses**
  Identify inventions, patent applications with date, and/or licenses that have resulted from the research. State whether an application is provisional or non-provisional and indicate the application number. Submission of this information as part of an interim research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award.

Nothing to report

- **Other Products**
  Identify any other reportable outcomes that were developed under this project. Reportable outcomes are defined as a research result that is or relates to a product, scientific advance, or research tool that makes a meaningful contribution toward the understanding, prevention, diagnosis, prognosis, treatment, and/or rehabilitation of a disease, injury or condition, or to improve the quality of life. Examples include:
  - *data or databases;*
  - *biospecimen collections;*
  - *audio or video products;*
  - *software;*
  - *models;*
  - *educational aids or curricula;*
  - *instruments or equipment;*
  - *research material (e.g., Germplasm; cell lines, DNA probes, animal models);*
  - *clinical interventions;*
  - *new business creation; and*
  - *other.*

Nothing to report

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?
Provide the following information for: (1) PDs/PIs; and (2) each person who has worked at least one person month per year on the project during the reporting period, regardless of the source

of compensation (a person month equals approximately 160 hours of effort). If information is unchanged from a previous submission, provide the name only and indicate "no change."

Example:

Name: *Mary Smith*
Project Role: *Graduate Student*
Researcher Identifier (e.g. ORCID ID): *1234567*
Nearest person month worked: *5*

Contribution to Project: *Ms. Smith has performed work in the area of combined error-control and constrained coding.*
Funding Support: *The Ford Foundation (Complete only if the funding support is provided from other than this award).*

Name: *Mark Pitkin*
Project Role: *PI*
Researcher Identifier (e.g. ORCID ID): *L-7934-2017*
Nearest person month worked: *5*
Contribution to Project: *Dr. Pitkin has directed all aspects of the project*

Name: *Grigory Raykhtsaum*
Project Role: *Director of Engineering*
Nearest person month worked: *3*
Contribution to Project: *Mr. Raykhtsaum was responsible for development and manufacturing of the SBIP-PNI pylons for animal studies*

Name: *Charles Cassidy*
Project Role: *Investigator*
Nearest person month worked: *0.1*
Contribution to Project: *Dr. Cassidy is a surgeon on the project performing two procedures in Year I.*

Name: *Boris Prilutsky*
Project Role: *Director of the Georgia Tech study*
Nearest person month worked: *1*
Contribution to Project: *Dr. Prilutsky has directed development of the powered prosthesis for animal studies and the animal trials with SBIP-PNI in Year I.*

Name: *Hangue Park*
Project Role: *Investigator/Postgraduate student of Georgia Tech*
Nearest person month worked: *10*
Contribution to Project: *Dr. Park developed the powered prosthesis for animal studies.*

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

If the active support has changed for the PD/PI(s) or senior/key personnel, then describe what the change has been. Changes may occur, for example, if a previously active grant has closed and/or if a previously pending grant is now active. Annotate this information so it is clear what has changed from the previous submission. Submission of other support information is not necessary for pending changes or for changes in the level of effort for active support reported previously. The awarding agency may require prior written approval if a change in active other support significantly impacts the effort on the project that is the subject of the project report.

New active support

Mark Pitkin, PI

a) Title of the project: R44 HD 090768 Large animal study on deeply porous transcutaneous pylon for direct skeletal attachment
b) Funding agency: NIH NCMRR
c) Project period: 09/26/2016 – 08/31/2018
d) Level (%) of effort in the project: 50%
e) Program Official: Louis A Quatrano
Email: quatranl@mail.nih.gov; Phone: (301) 402-4221 Fax: (301) 402-0832
f) The project is to develop and test new pylons and their implantation technique for direct skeletal attachment of leg prostheses. The goals are to increase integration of the pylons with skin and bone by developing new porous claddings with deep porosity and with Nano silver coating, developing technique of distraction implantation of pylons with side elements, and testing the Rolling Joint Foot and Ankle prosthesis with anticipation of minimizing bending moments from the pylon to the hosting bone.
g) There is no overlap with our current project

Grigory Raykhtsaum, Investigator/Director of Engineering

a) Title: R44 HD 090768 Large animal study on deeply porous transcutaneous pylon for direct skeletal attachment
b) Funding agency: NIH NCMRR
c) PI: Mark Pitkin
d) Project period: 09/26/2016 – 08/31/2018
e) Level (%) of effort in the project: 17%

Boris Prilutsky, PD for Georgia Tech study

a) Title: R01NS100928 Neural mechanisms of locomotion evoked by epidural stimulation of the spinal cord
b) Agency: NIH/NINDS
c) PI: Boris Prilutsky
d) Project Period: 07/15/2017-05/31/2022
e) Level of support: .12%
f) There is no overlap with our current project

What other organizations were involved as partners?
If there is nothing significant to report during this reporting period, state "Nothing to Report."

Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the research, exchanged personnel, or otherwise contributed.

1. DaVinci Biomedical Research, 20 Maple St, Lancaster, MA 01523
   - *Financial support: MR150015 Integration of the Residual Limb with Prostheses via Direct Skin-Bone-Peripheral Nerve Interface*
   - *Facilities and personnel collaborating on animal studies with pigs.*
2. Advanced Manufacturing Products (ADMA), Hudson, OH
   - *Financial support: MR150015 Integration of the Residual Limb with Prostheses via Direct Skin-Bone-Peripheral Nerve Interface*
   - *Facilities and personnel for sintering titanium SBIP-PNI pylons with selected specifications for animal studies*
3. Georgia Institute of Technology, Atlanta, GA
   - *Financial support: MR150015 Integration of the Residual Limb with Prostheses via Direct Skin-Bone-Peripheral Nerve Interface*
   - *Conducting animals study with cats wearing powered prostheses following DSA*
4. T3 Labs, Atlanta, GA 30313
   - *Financial support: MR150015 Integration of the Residual Limb with Prostheses via Direct Skin-Bone-Peripheral Nerve Interface*
   - *Facilities and personnel collaborating on animal studies with cats.*

8. SPECIAL REPORTING REQUIREMENTS

COLLABORATIVE AWARDS: For collaborative awards, independent reports are required from BOTH the Initiating PI and the Collaborating/Partnering PI. A duplicative report is acceptable; however, tasks shall be clearly marked with the responsible PI and research site. A report shall be submitted to **https://ers.amedd.army.mil** for each unique award.

Nothing to report

QUAD CHARTS: If applicable, the Quad Chart (available on https://www.usamraa.army.mil) should be updated and submitted with attachments.

9. APPENDICES:

Attach all appendices that contain information that supplements, clarifies or supports the text. Examples include original copies of journal articles, reprints of manuscripts and abstracts, a curriculum vitae, patent applications, study questionnaires, and surveys, etc.

Nothing to report