AWARD NUMBER: W81XWH-15-1-0232

TITLE: Reference Models for Multi-Layer Tissue Structures

PRINCIPAL INVESTIGATOR: Ahmet Erdemir, PhD

CONTRACTING ORGANIZATION: Cleveland Clinic
Cleveland, OH 44195

REPORT DATE: September 2016

TYPE OF REPORT: Annual

PREPARED FOR: U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

DISTRIBUTION STATEMENT: Approved for Public Release;
Distribution Unlimited

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE
September 2016

2. REPORT TYPE
Annual

3. DATES COVERED
1 Sep 2015 - 31 Aug 2016

4. TITLE AND SUBTITLE
Reference Models for Multi-Layer Tissue Structures

5a. CONTRACT NUMBER

5b. GRANT NUMBER
W81XWH-15-1-0232

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Ahmet Erdemir

E-Mail: erdemira@ccf.org

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Cleveland Clinic Foundation
9500 Euclid Avenue
Cleveland, OH 44195-0001

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U.S. Army Medical Research and Materiel Command
Fort Detrick, Maryland 21702-5012

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT The aims of this work are i) to establish an online platform to curate, distribute, and reuse data and models of multi-layer tissue structures of musculoskeletal extremities, ii) to collect and disseminate anatomical and mechanical data for building and validating reference models, iii) to build, validate, and disseminate mechanically advanced reference models representative of nonlinear material properties and realistic anatomy, and iv) to build and evaluate fast and mechanically simplified yet visually and haptically realistic surrogate models to be used for surgical simulation. At the time when this report was written, a prototype of a web based data management system was developed, an ultrasound system was instrumented with a force transducer, and in vivo testing has started to acquire the thickness and indentation response of skin, fat, muscle layers of the legs and arms. This comprehensive data will provide the foundations for development of authentic and individualized models for simulation of haptics of musculoskeletal extremities for training.

15. SUBJECT TERMS
musculoskeletal, muscle, skin, fat, tissue interface, extremity injury, extremity response, surface mechanics, ultrasound, surgical simulation, finite element analysis

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	Unclassified	24	USAMRMC
					19b. TELEPHONE NUMBER *(include area code)*

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1. INTRODUCTION

High incident rates of combat injuries to the musculoskeletal extremities dictate the immediate need to understand and simulate contact mechanics and internal mechanical interactions of layered tissue organization of these body regions. The mechanical response of multi-layer tissue structures around the legs and arms is a function of the underlying muscle, skin, and fat tissues and the junctions in between. With the knowledge of individual tissue material properties, layered anatomy, and the mechanical capacity of tissue interfaces, it will be possible to develop computational models to conduct descriptive and predictive simulations. Such in silico analyses have utmost importance to develop and evaluate diagnostic strategies, surgical interventions, and protective equipment. The overall goal of this study is to establish the founding knowledge, data and models for the mechanics of multi-layer tissue structures of the limbs, particularly of the lower and upper legs and arms. By delivering this lacking information, the activity will promote scientific research in layered tissue structures and allow reliable virtual surgery simulations for clinical training and certification. All data and models will be provided in an open and freely available manner to maximize outreach of this information.

2. KEYWORDS

musculoskeletal, muscle, skin, fat, tissue interface, extremity injury, extremity response, surface mechanics

3. ACCOMPLISHMENTS

What were the major goals of the project?

Major milestones and relevant tasks of the project as stated in the Statement of Work are provided below.

YEAR 1	***Milestone.*** Web-based interfaces for data curation, queryable data and model databases. *Tasks.* Web design and programming to incorporate new features in online collaboration infrastructure. *Deliverables.* Prototype of web-based tools for data curation and analysis, model assembly, simulation, and post-processing.
YEAR 1	***Milestone.*** In vivo multi-layer tissue anatomy and indentation mechanics. *Tasks.* Recruitment of human subjects, acquisition of demographics, anthropometric measurements, ultrasound measurements of layered tissue thicknesses of legs and arms, indentation with ultrasound. *Deliverables.* Data on gross anatomy and indentation mechanics of lower and upper legs and arms of 100 human subjects.
YEARS 1-2	***Milestone.*** In vitro multi-layer tissue anatomy, mechanical properties, and indentation mechanics. *Tasks.* Acquisition of cadaver specimens, magnetic resonance imaging of cadaver legs and arms, indentation with ultrasound, sampling of skin, muscle, fat tissues and junctions, mechanical testing of tissues and junctions. *Deliverables.* Data on detailed anatomy, tissue and tissue-interface properties, and indentation mechanics of cadaver lower and upper legs and arms (10 specimens for each region).
YEAR 2	***Milestone.*** In vitro quantification of tool forces during surgery of multi-layer tissue structures. *Tasks.* Acquisition of cadaver upper leg specimens, mechanical manipulations using instrumented tools, magnetic resonance imaging, sampling and testing of skin, muscle, fat and their junctions. *Deliverables.* Data on mechanical and haptic responses of 10 cadaver upper leg specimens during surgical procedures.
YEAR 2	***Milestone.*** Physiologically realistic, fully specimen-specific, nonlinear reference models. *Tasks.* Finite element analysis of non-linear mechanics of cadaver specimens. *Deliverables.* Specimen- and region-specific reference models of upper and lower legs and arms confirmed against indentation data (8 models - 4 regions, 1 male and 1 female representative donors).
YEAR 2	***Milestone.*** Physiologically realistic, partially subject-specific, nonlinear reference models. *Tasks.* Finite element analysis of non-linear mechanics of multi-layer tissue regions of human subjects. *Deliverables.* Partially subject- and region-specific reference models of upper and lower legs and arms confirmed against indentation data (8 models - 4 regions, 1 male and 1 female representative subjects).
YEAR 3	***Milestone.*** Computationally efficient surrogate models for multi-layer tissue structures. *Tasks.* Model reduction and simplification to develop cost-effective models of surface manipulation of multi-layer tissues. *Deliverables.* Specimen- (or subject) and region-specific surrogate models of upper and lower legs and arms confirmed against indentation data and reference models (16 models - 4 regions, 2 male and 2 female representatives).
YEAR 3	***Milestone.*** Demonstration of efficient surrogate models of multi-layer tissue structures. *Tasks.* Model reduction and simplification to develop cost-effective models of surgical manipulation. *Deliverables.* Specimen-specific surrogate models of upper legs confirmed against data from lifelike manipulations of surgical procedures (2 models - 1 male and 1 female representative donors).
YEARS 1-3	***Milestone.*** Population and dissemination of data and models. *Tasks.* Routine utilization of web-based interfaces to curate data, populate databases, and disseminate models. *Deliverables.* Free and open access to all deliverables of the project.

What was accomplished under these goals?

Milestone. *Web-based interfaces for data curation, queryable data and model databases.*

Major Activities. A major activity was the development of a prototype for data management and query. Other activities included regular discussions between Cleveland Clinic team and Stanford University team, and ongoing documentation on the project wiki to develop specifications and infrastructure for data management and database systems. Testing of the prototype has also started.

Specific Objectives. Specific goals of the reporting period in regard to this milestone were twofold. First objective was the documentation of complete specifications for data management system. The second objective was to implementation of a prototype data management system for upload and organization of raw data.

Significant Results. Documentation of data management system and databases has been evolving. An initial prototype for data management was launched on a testing server and ready for usability testing. The system allows upload and organization of raw data and automated population of metadata. A query system is also provided to search data that meet user-specified criteria. See Figure 1 for more detail.

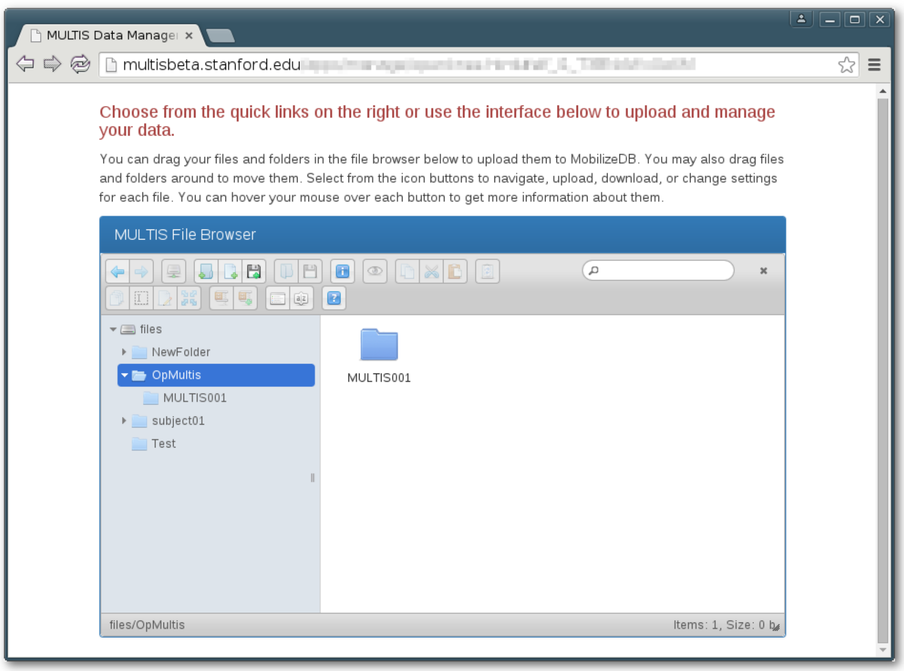


Figure 1. A prototype of the web-based data management interface was deployed for the project. It is possible to drag and drop subject folders to the cloud based storage. Querying of data is also possible.

Other Achievements. *None noted.*

Milestone. *In vivo multi-layer tissue anatomy and indentation mechanics.*

Major Activities. Major activities included documentation of data collection procedures and full integration of load transducer and ultrasound imaging systems. In addition, mock-up sessions were held to ensure readiness for large scale in vivo testing (100 subjects). Various issues for the data collection software and in experimentation procedures were identified through these mock-up sessions and were addressed. Testing of the subjects has started.

Specific Objectives. Specific goals of the reporting period in regard to this milestone were multiple and related to overall readiness to start experimentation on human subjects: i) detailed documentation of standard operating procedures for in vivo anatomical and mechanical characterization using ultrasound, ii) update of the data collection engine for simultaneous collection of ultrasound probe forces and orientations, and of the user interface for subject data entry, automated progression of data collection, and visualization for confirmation, iii) manufacturing of the handle to establish physical connectivity between ultrasound probe and force transducer allowing operator-friendly handling of the ultrasound probe during imaging, iv) commencement of testing for anatomical and mechanical characterization of skin-muscle-fat layers of legs and arms on live subjects.

Significant Results. Documentation of standard operating procedures is complete. A working version of the instrumented ultrasound system (with a load transducer) is now available. A handle to connect the ultrasound probe and force transducer was designed and manufactured (Figure 2). Initial usability testing of the system was performed, indicating necessary updates to the data collection software and experimentation protocols. Many of these updates were already implemented. Additional mock up sessions were conducted. Testing on human subjects has commenced (Figure 3). Software for data analysis has been developed for assisted measurement of tissue thickness acquired during anatomical imaging and indentation (Figure 4).

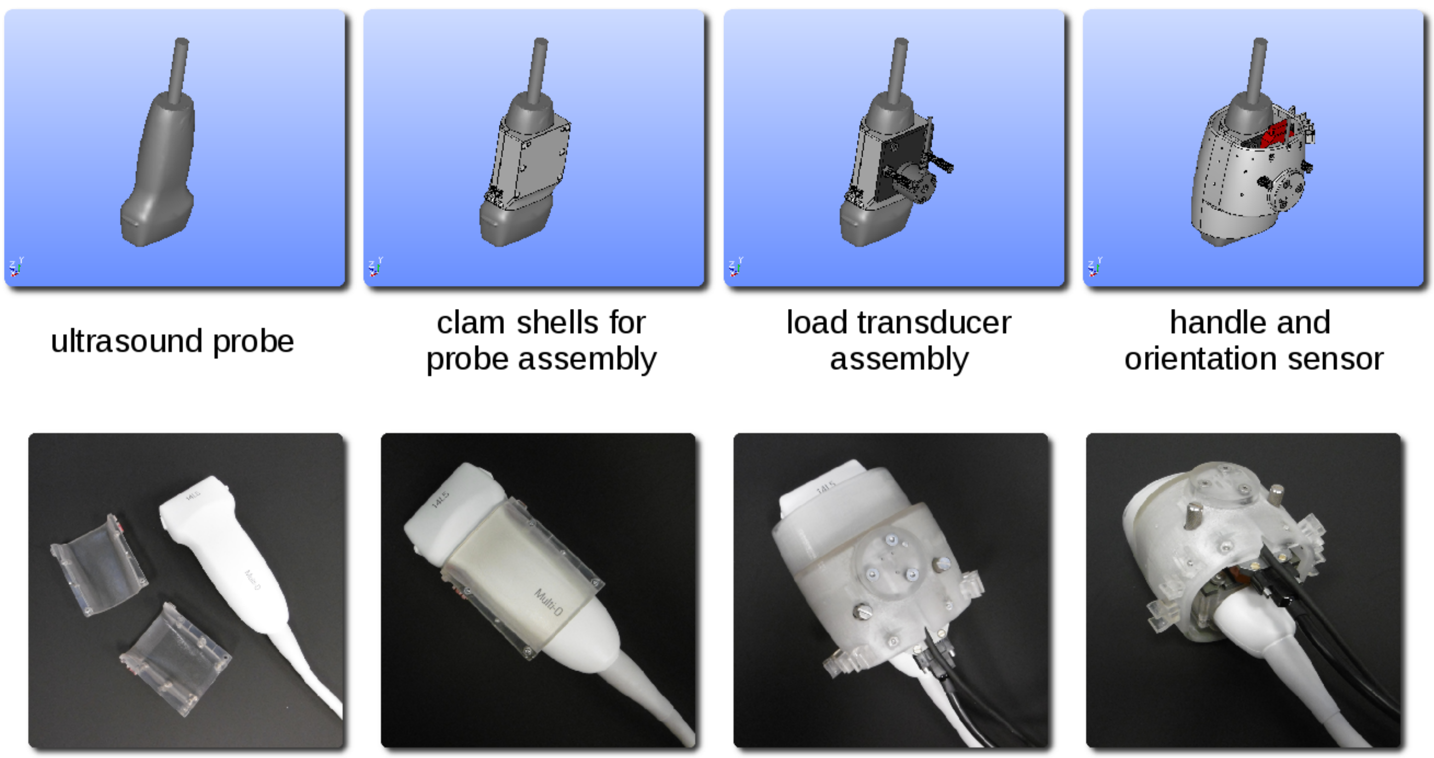


Figure 2. The design of the ultrasound probe – load transducer interface is shown at the top. The interface was manufactured (bottom row) and is currently in use.

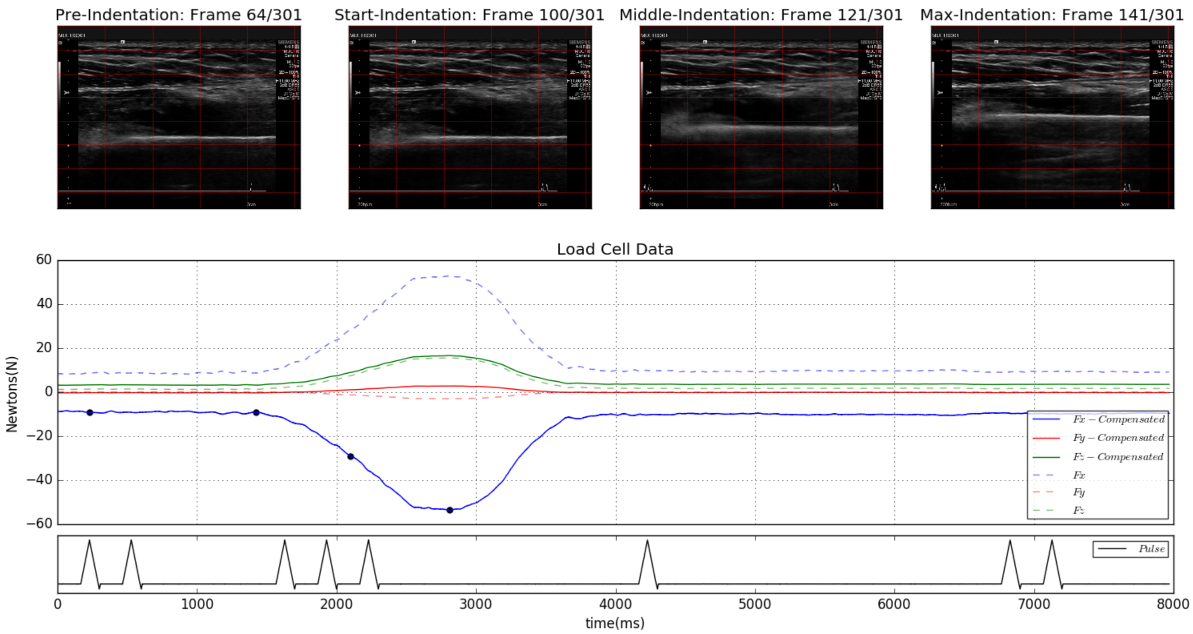


Figure 3. Sample indentation data collected on a subject. Deformation of the tissue can be seen on the top row. Time history of indentation forces are on the second row and the trial identification and synchronization signal is on the bottom row.

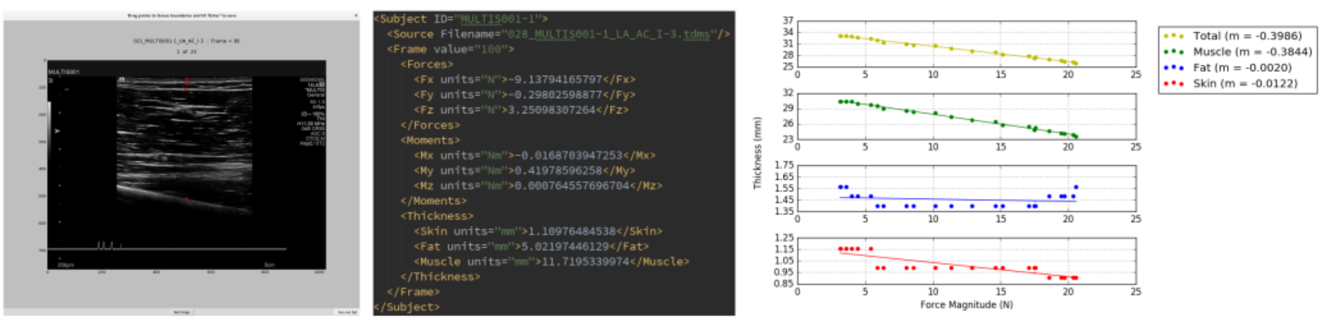


Figure 4. A software package was developed in Python for assisted measurement of skin, fat, and muscle thickness from ultrasound images. Measurements are saved as an XML file along with corresponding loading. On the right, thickness as a function of indentation force is displayed.

Other Achievements. None noted.

Milestone. *In vitro multi-layer tissue anatomy, mechanical properties, and indentation mechanics.*

Major Activities. Major activities included regular discussions within the Cleveland Clinic Core team and with the collaborating surgeon, and ongoing documentation on the project wiki to develop specifications for cadaver experimentation and for equipment integration. A recently hired research engineer was assigned to lead the activities for in vitro testing.

Specific Objectives. Specific goals in regard to this milestone were: i) documentation and evaluation of magnetic resonance imaging protocols for characterization of detailed multi-layer tissue anatomy, ii) initial design of a testing bench for recording of biomechanical metrics and digital video during mechanical manipulation of cadaver specimens.

Significant Results. Outcomes, described above for the design and implementation of an integrated ultrasound imaging and indentation force data collection system, are also relevant to the specific objectives of this milestone. Detailed documentation of standard operating procedures for in vitro testing has started and provided initial designs for cadaver experimentation setup including testing room configuration (Figure 5). Sample magnetic resonance images were collected (Figure 6).

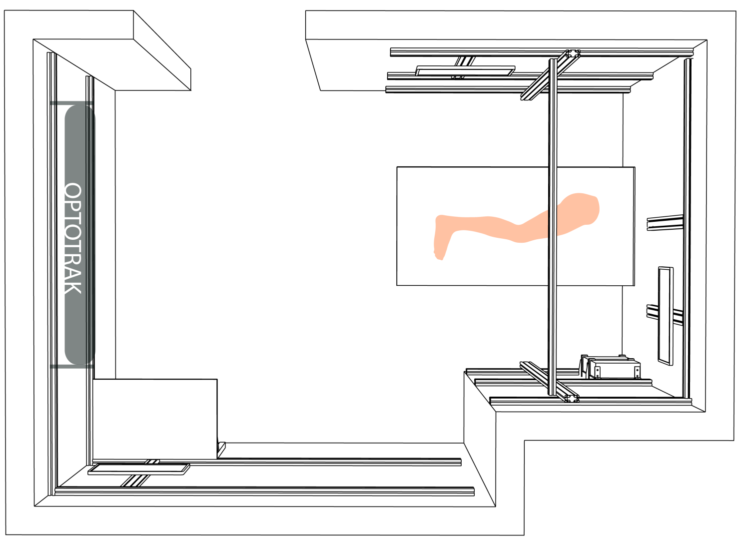


Figure 5. In vitro testing room was configured to accommodate measurements on cadaver limbs using multiple data acquisition modalities, e.g. tracking of ultrasound probe location using Optotrak.

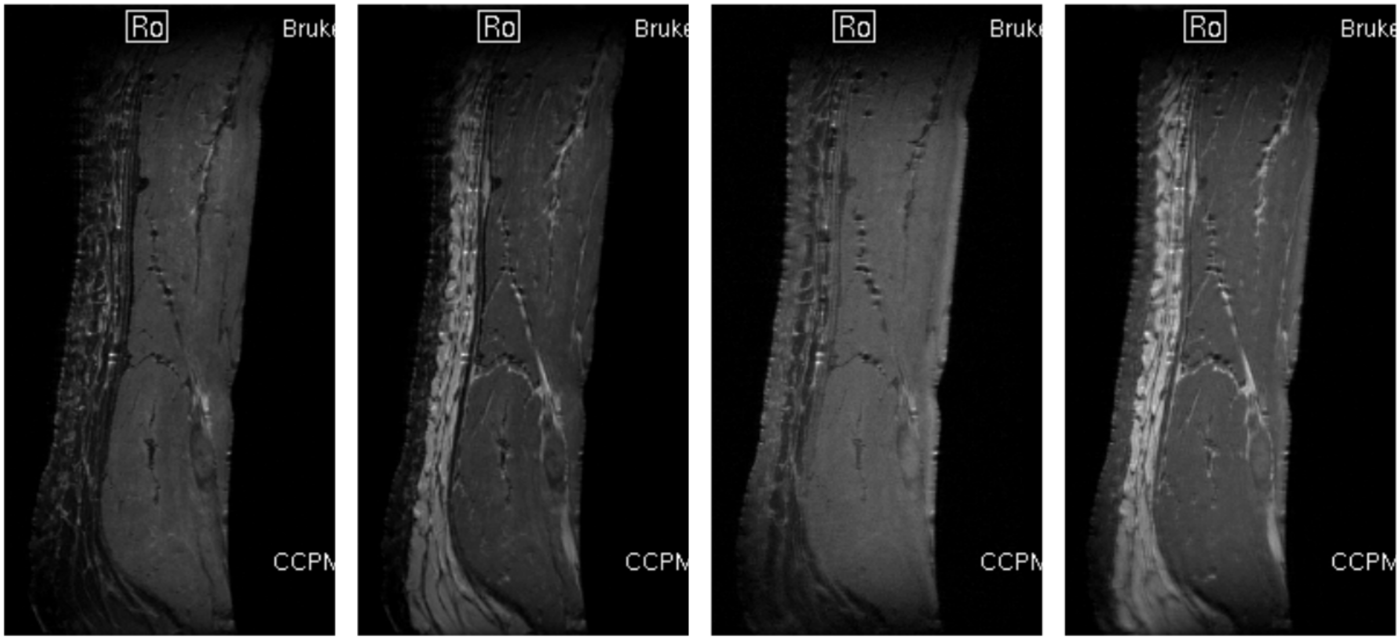


Figure 6. Magnetic resonance imaging of a skin, fat, muscle tissue sample illustrates the variations of tissue contrast as a function of image settings.

Other Achievements. None noted.

Milestone. In vitro quantification of tool forces during surgery of multi-layer tissue structures.

Major Activities. Major activities included identification of surgical tools and their handling. Specifications for and design of load transducer integration on surgical tools for measurement of surgical forces were other activities.

Specific Objectives. Specific goals in regard to this milestone were: i) documentation of surgical tools, ii) initial design for integration of a load transducer for recording of tool forces during surgical acts.

Significant Results. Expected loading ranges were documented in mock-up tests for identification and acquisition of spatial load transducers (Figure 7). A handle to connect surgical tool tips to a force transducer was designed and manufactured (Figure 8).

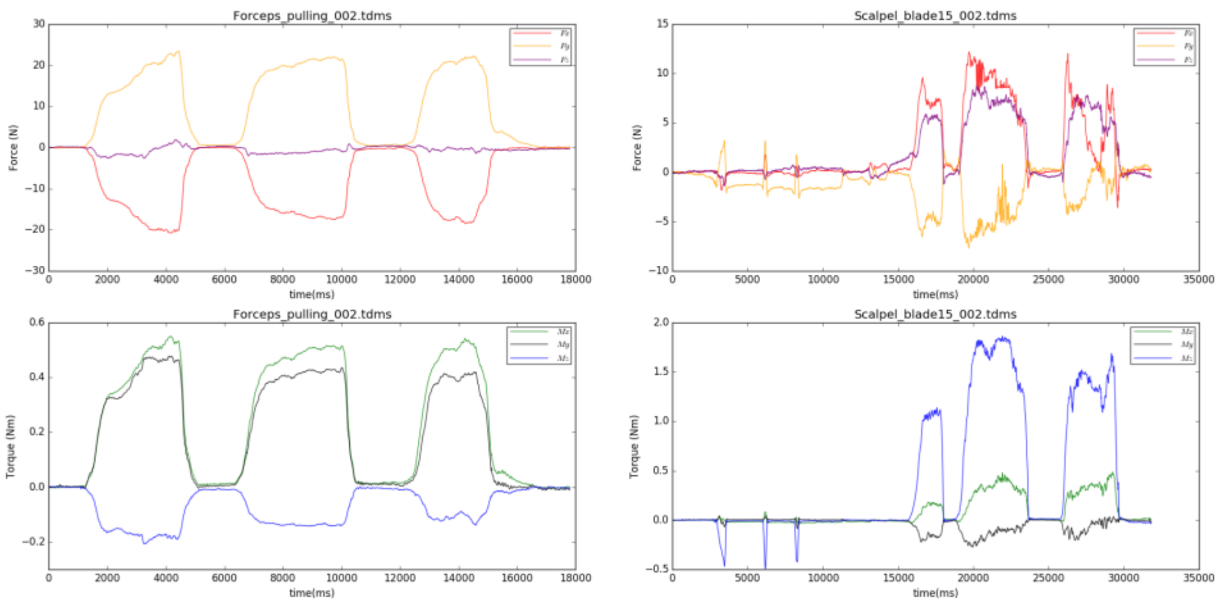


Figure 7. In mock-up trials, surgical tool force ranges were estimated, e.g. for pulling forces of forceps (on the left) and for cutting forces of a scalpel blade (on the right)

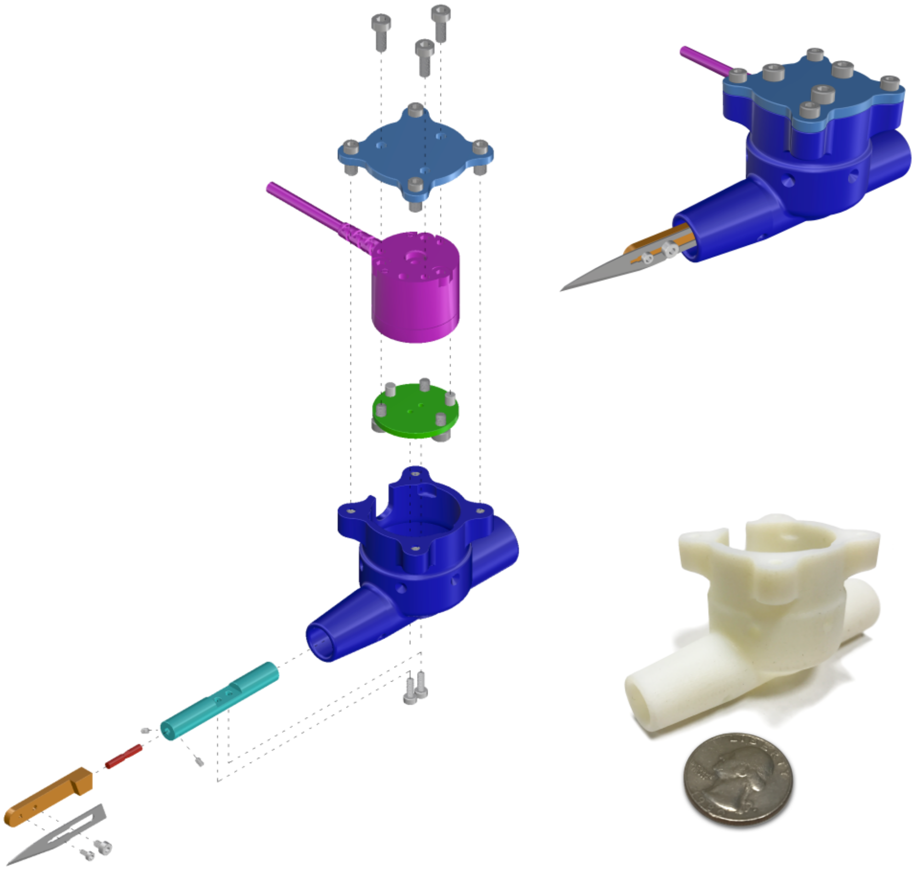


Figure 8. A housing was designed to assemble a load transducer with a surgical tool tip (a surgical blade is shown). The housing was manufactured. The assembly will allow measurement of forces during surgical acts.

Other Achievements. None noted.

Milestone(s). *Reference models and surrogate models.*

Major Activities. Major activities included training on simulation software, understanding software feature requirements for simulation of multi-layer tissue mechanics, and development of specifications.

Specific Objectives. Specific goals in regard to this milestone were: i) to develop know-how relevant to modeling of skin, fat, muscle layers of musculoskeletal extremities, ii) to start developing procedures for generation of model components to feed reference and surrogate models.

Significant Results. Predictive performances of FEBio, finite element analysis software for reference models, and SOFA, surgical simulation software for surrogate models, were compared for simplified models (Figure 9). Simple yet topologically similar models of skin, fat, muscle layers were developed in SOFA (Figure 10).

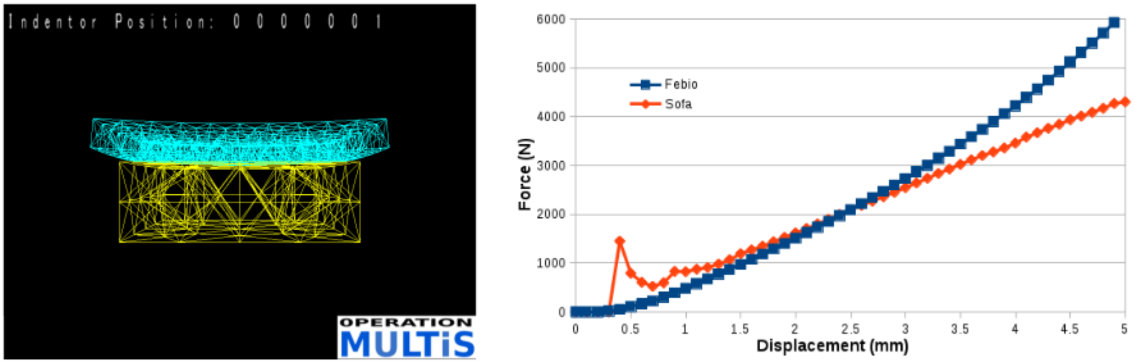


Figure 9. A simple indentation problem was devised to compare indentation response, as predicted by FEBio and SOFA. FEBio will be used for finite element analysis using reference models. SOFA will be used for surgical simulations.

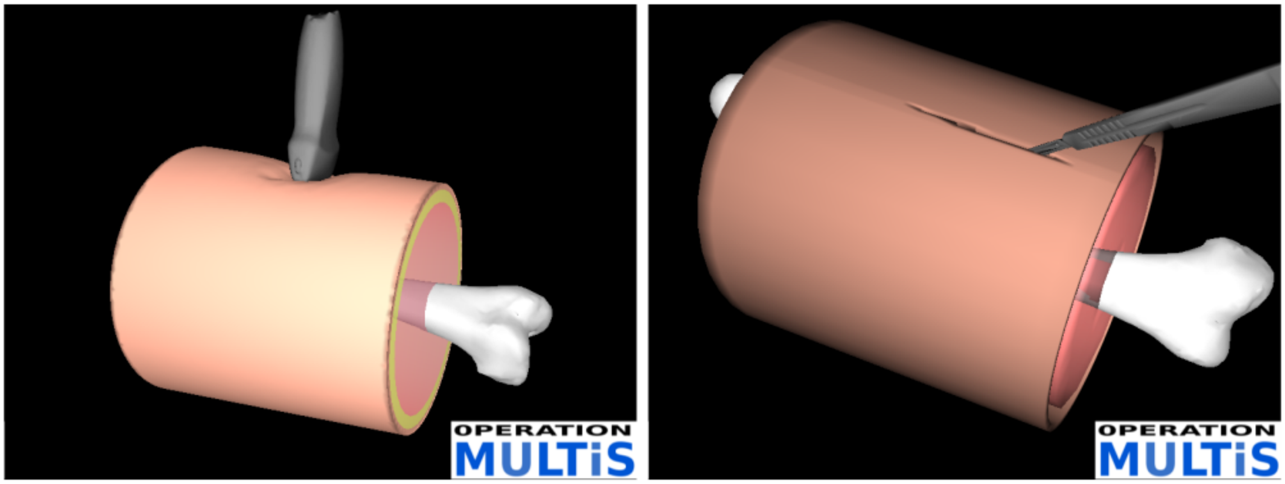


Figure 10. Simplified yet topologically layered models used for implementation of anticipated loading conditions in SOFA. On the left, indentation with an ultrasound probe is shown. On the right, cutting with a surgical blade is displayed.

Other Achievements. None noted.

What opportunities for training and professional development has the project provided?

Nothing to report.

How were the results disseminated to communities of interest?

The project implements an open development approach. At this stage of the project, all information relevant to experimentation and modeling procedures and infrastructure development (data, designs, models, code, documentation) are publicly accessible at the project website, https://simtk.org/projects/multis.

What do you plan to do during the next reporting period to accomplish the goals?

Milestone. *Web-based interfaces for data curation, queryable data and model databases.*

- Evaluation of the data management system prototype for upload, organization, and dissemination of raw data.
- Initiation of prototype development for databases of derivative data.
- Population of data management system with in vivo testing data.

Milestone. *In vivo multi-layer tissue anatomy and indentation mechanics.*

- Continuation (possibly finalization) of data collection.

Milestone. *In vitro multi-layer tissue anatomy, mechanical properties, and indentation mechanics.*

- Completion of testing bench construction for recording of biomechanical metrics and digital video during mechanical manipulation of cadaver specimens.
- Commencement of data collection.

Milestone. *In vitro quantification of tool forces during surgery of multi-layer tissue structures.*

- Completion of surgical tool instrumentation.

Milestone(s). *Reference models and surrogate models.*

- Detailed documentation of specifications for modeling and simulation.

4. IMPACT

What was the impact on the development of the principal discipline(s) of the project?

The development of a load transducer instrumented ultrasound provides the capacity to measure internal deformations of organs as a function of external loading. In biomechanics, the principal discipline of the the project, this tool will help quantify anatomical and mechanical variations of multi-layer tissues of musculoskeletal extremities, which can be used for development of models for surgical simulations, to design protective gear for musculoskeletal extremities,.for consumer product design (performance clothing), and to form the basis for scientific and clinical discoveries related to the function of multi-layer tissues (etiology and management of pressure ulcers).

What was the impact on other disciplines?

As part of the project, a data management system has been prototyped. This web-based system and the storage resources can be utilized by projects in any other discipline that requires management and dissemination of rich data.

What was the impact on technology transfer?

The project resulted in two primary technological advancements that may have an impact on public use. First, a robust engineering solution to integrate a load transducer to any ultrasound system for freehand measurement of ultrasound probe forces during imaging was developed. The know-how for this systems is currently documented in the publicly accessible wiki pages of the project. Second, a proof-of-concept for a data management system was developed. This system can be adapted for data rich scientific and engineering projects for organization and orderly dissemination of information. The system will be launched as part of the project and will likely be part of a feature set at SimTK, a publicly accessible platform for biomedical computing.

What was the impact on society beyond science and technology?

The project adapts an open science approach. Experimentation and modeling workflows and infrastructure are documented publicly as they develop. Know-how to conduct scientific work and to build resources are part of these documentation. This will likely impact scientific practice and its perception in the society.

5. CHANGES/PROBLEMS

Changes in approach and reasons for change

Nothing to report.

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

There were delays to start in vivo testing of musculoskeletal extremities and to prepare for in vitro testing, which potentially caused a shift in timeline by a quarter. These delays were a consequence of delays in hiring staff (noted below). Now that the project has successfully recruited three engineers (on December 14, 2015, May 15, 2016, and August 29, 2016), the activities will continue at their anticipated rate.

Changes that had a significant impact on expenditures

Delayed recruitment and sub-award chargebacks had a significant impact on expenditure rate. The team also postponed acquisition of a portable ultrasound system and is using a higher quality system available on loan to the Department of Biomedical Engineering, Cleveland Clinic. As a result of delays in in vitro testing, purchasing of a mechanical tissue testing system was postponed. The rate of expenditures is expected to return to planned levels due to recent recruitments: a full time senior research engineer (started on Dec 14, 2015, for modeling & simulation), a full time research engineer (started on May 16, 2016, for in vitro experimentation), and a full time research engineer (started on August 29, 2016 for data analysis). The project also recruits part time engineers from BioRobotics and Mechanical Testing Core, Cleveland Clinic for hardware/software integration tasks of in vivo and in vitro experimentation and has acquired services from Medical Device Solutions, Cleveland Clinic for design tasks. Equipment purchases and subaward chargebacks are also expected to be completed in an orderly fashion.

Significant changes in use or care of human subjects, vertebrate animals, biohazards, and/or select agents

Significant changes in use or care of human subjects

Nothing to report. Use and care of human subjects are ongoing in an orderly fashion. Current status is summarized below.

Human Use Regulatory Protocols

1 human subject research protocol will be required to complete the Statement of Work.

<u>Protocol of total:</u> 1

Human Research Protection Office (HRPO) assigned A-number:A-18650.a (Cleveland Clinic Site) & A-18650.b (Stanford University Site)

Title: Reference Models for Multi-Layer Tissue Structures

Target required for clinical significance:100 human subjects and 50 cadaver specimens

Target approved for clinical significance: 100 human subjects and 50 cadaver specimens

<u>Submitted to and Approved by:</u>

- IRB # 14-1597 – Reference Models for Multi-Layer Tissue Structures: received on 12/18/2014, approved for the period 12/23/2014 through 12/22/2015 (Cleveland Clinic Site IRB for human subjects testing)

- IRB # 14-1597 – Reference Models for Multi-Layer Tissue Structures: received revised protocol version 2 on 01/16/2015, approved through 12/22/2015 (Clinic Clinic Site IRB amendment to the human testing application to include cadaveric testing section)
- IRB # 34361 – Reference Models for Multi-Layer Tissue Structures: notice of determination dated 05/26/2015 indicating that the project does not meet the federal regulatory definition of human subject research (Stanford University IRB in regard to dissemination of de-identified data)
- HRPO Log Number A-18650.a (Cleveland Clinic Site) and HRPO Log Number A-18650.b (Stanford University Site): approved on 06/22/2015.
- IRB # 14-1597 – Reference Models for Multi-Layer Tissue Structures: renewal application received on 12/01/2015, approved for the period 12/23/2015 through 12/22/2016 (Cleveland Clinic Site IRB for human subjects testing)
- HRPO acknowledged receipt of the Cleveland Clinic Site IRB approval of the renewal application on 12/17/2015.

Status:

- 2 subjects have been recruited.

Use of Human Cadavers for Research Development Test & Evaluation (RDT&E), Education or Training

1 RDT&E, education or training activity involving human cadavers will be performed to complete the Statement of Work.

- Title: Reference Models for Multi-Layer Tissue Structures
- Relevant milestone: In vitro multi-layer tissue anatomy, mechanical properties, and indentation mechanics.
- Date of the activity: Experiments have not been performed yet. The activity is at a design phase.
- Responsible individual: Ahmet Erdemir (Principal Investigator)
- Brief description: Indentation of cadaver legs and arms using instrumented ultrasound probe; mechanical testing to identify properties of muscle, skin, and fat layers of extremities – a targeted total of 40 specimens.

Significant changes in use or care of vertebrate animals

Nothing to report.

Significant changes in use of biohazards and/or select agents

Nothing to report.

6. PRODUCTS

Publications, conference papers, and presentations

Nothing to report.

Website(s) or other Internet site(s)

https://simtk.org/projects/multis
This is the project website launched through the SimTK infrastructure. SimTK is maintained and upgraded by our collaborators at Stanford University to assist organization, collaboration, dissemination, and visibility. The project website includes various components: a list of team members, a downloads section to disseminate resources, a documents section to provide documents, a wiki for collaboration, a publications area for listing abstracts, articles, etc. generated as part of the project, a news list, forums for discussions, and a source code repository with a version control system to assist software development. Within the goals of this project, SimTk.org infrastructure will be improved by our collaborators at Stanford University to provide services for data management and databases. All materials in the project site are publicly available.

https://simtk.org/svn/multis/
Source code repository includes data analysis code and models under development (public access).

https://simtk.org/plugins/moinmoin/multis/
The wiki is part of the project website. Nonetheless, it is worth mentioning in here as it provides dynamic documentation of project activities. At the wiki, one can find the narrative of the grant proposal (as submitted to the US Army), the roadmap of the project, an evolving set of specifications and infrastructure to accomplish the project goals, and minutes of group meetings.. All wiki pages are accessible publicly. Highlights of matured and developing documents of infrastructure that has been deployed for the project and for for experimentation, data analysis, and modeling specifications are listed below:

https://simtk.org/plugins/moinmoin/multis/Infrastructure/InstrumentedUltrasound
https://simtk.org/plugins/moinmoin/multis/Infrastructure/InstrumentedSurgicalTools
https://simtk.org/plugins/moinmoin/multis/Infrastructure/TestingRoom
https://simtk.org/plugins/moinmoin/multis/Specifications/InVivoTesting
https://simtk.org/plugins/moinmoin/multis/Specifications/InVitroTesting
https://simtk.org/plugins/moinmoin/multis/Specifications/DataAnalysis
https://simtk.org/plugins/moinmoin/multis/Specifications/IndentationModeling
https://simtk.org/plugins/moinmoin/multis/Specifications/SofaBasics

Technologies or techniques

Technologies developed as part of this project includes:

Load Transducer Instrumented Ultrasound (LINUS)
This is a customizable technology for physical integration of and signal communication between an ultrasound system and a spatial load transducer.
Know-how is described in https://simtk.org/plugins/moinmoin/multis/Infrastructure/InstrumentedUltrasound.

System is currently in use by the research team. Geometric modeling for physical assembly will be available at the project site. Publications are planned.

Load Transducer Instrumented Surgical Tools

This is a customizable technology for physical integration of surgical tool tips with a spatial load transducer for recording of forces during surgical acts.

Know-how is described in https://simtk.org/plugins/moinmoin/multis/Infrastructure/InstrumentedSurgicalTools.

Designs were completed. Manufacturing is in progress. Geometric modeling for physical assembly will be available at the project site. Publications are planned.

Operation MULTIS Data Management System

This is customizable data management system and data querying system, designed for the project.

Prototype is available at http://multisbeta.stanford.edu.

Some design considerations were noted at

https://simtk.org/plugins/moinmoin/multis/Specifications/DataManagement.

System will be widely available at SimTK site.

Inventions, patent applications, and/or licenses

Nothing to report.

Other Products

Load Transducer Instrumented Ultrasound Data Analysis Software

This is a Python based software for association and time alignment of ultrasound images and load measurements and for assisted identification of skin, fat, and muscle thickness during anatomical imaging or indentation.

Know-how is described in https://simtk.org/plugins/moinmoin/multis/Specifications/DataAnalysis.

A working prototype is available in the source code repository at https://simtk.org/svn/multis/.

Software is currently in use by the research team. Publications are planned.

7. PARTICIPANTS & OTHER COLLABORATING ORGANIZATIONS

What individuals have worked on the project?

The activity included effort from personnel in the Department of Biomedical Engineering at the Cleveland Clinic, in the Multidisciplinary Simulation Center at the Cleveland Clinic, and at Simbios, NIH Center for Biomedical Computation at Stanford University. A list of these individuals are provided in following.

Name:	Ahmet Erdemir
Project Role:	Principal Investigator
Research Identifier:	N/A
Nearest person month worked:	4
Contribution to Project:	Dr. Erdemir leads the scientific and engineering direction of the proposed project. He provides supervision for all project members and gives insight to the collaborating team at Stanford University for the development of web-based interfaces and online databases.

Name:	Tammy Owings
Project Role:	Project Scientist
Research Identifier:	N/A
Nearest person month worked:	9
Contribution to Project:	Dr. Owings is for the preparations for experimentation on human subjects. She specifically worked on the development of in vivo testing protocols and has been collecting in vivo data.

Name:	Benjamin Landis
Project Role:	Senior Research Engineer
Research Identifier:	N/A
Nearest person month worked:	12 (started on December 14, 2015)
Contribution to Project:	Mr. Landis is responsible for establishing the modeling and simulation workflows of the project. He has been working with simulation software (both for nonlinear finite element analysis and for surgical simulations) to understand implementation of simulation features necessary for the project. He has been building simple models to guide prospective development of anatomically realistic and mechanically authentic models of the musculoskeletal tissue layers.

Name:	Tyler Schimmoeller
Project Role:	Research Engineer
Research Identifier:	N/A
Nearest person month worked:	12 (started on May 15, 2016)
Contribution to Project:	Mr. Schimmoeller has been familiarizing with the workflow and tools relevant to in vitro testing of multi-layer tissue structures. He has been tasked with development of specifications and experimentation setup in this regard. He also designs physical interfaces for instrumentation of surgical tools.

Name:	Erica Morrill
Project Role:	Senior Research Engineer
Research Identifier:	N/A
Nearest person month worked:	12 (started on August 29, 2016)
Contribution to Project:	Ms. Morrill is responsible from data analysis. Her activities include development of software for extraction of tissue thickness and indentation forces from data acquired by the instrumented ultrasound system.

Name:	Robb Colbrunn
Project Role:	Project Scientist
Research Identifier:	N/A
Nearest person month worked:	2
Contribution to Project:	Dr. Colbrunn leads efforts on the integration of ultrasound and force transducer systems. He also works data collection systems for measurement of surgical tool forces.

Name:	Tara Bonner
Project Role:	Senior Research Engineer
Research Identifier:	N/A
Nearest person month worked:	2
Contribution to Project:	Ms. Bonner has developed and supported upgrades to the user interface for measurement of forces during ultrasound imaging.

Name:	John-Eric Jelovsek
Project Role:	Co-Investigator
Research Identifier:	N/A
Nearest person month worked:	1
Contribution to Project:	Dr. Jelovsek continued providing advice on surgical simulation systems, surgical tool handling, ultrasound imaging of tissues, and various aspects of in vivo testing setup.

Name:	Scott Delp
Project Role:	Principal Investigator on Subcontract
Research Identifier:	N/A
Nearest person month worked:	0
Contribution to Project:	Dr. Delp continued to provide overall direction for upgrade of the SimTK in relevance to this project.

Name:	Joy Ku
Project Role:	Project Manager on Subcontract
Research Identifier:	N/A
Nearest person month worked:	1
Contribution to Project:	Dr. Joy has led the efforts to launch an initial prototype for web-based data management and data querying in SimTK infrastructure.

Name: Mike Wong
Project Role: Consultant on Subcontract
Research Identifier: N/A
Nearest person month worked: 1
Contribution to Project: Mr. Wong provides programming support for prototyping of web-based data management and data querying in SimTK infrastructure.

Has there been a change in the active other support of the PD/PI(s) or senior/key personnel since the last reporting period?

Since last reporting, other support for Ahmet Erdemir, PhD (Principal Investigator) has changed. Specifically, the following activities, in which Dr. Erdemir is involved, were funded. These changes do not impacts the effort on the project that is the subject of the project report.

R01AR068278 (Li) 07/01/2015 – 06/30/2020 0.6 calendar
National Institutes of Health / NIAMS $517,084 (Year 1 total costs)
Biomechanical Treatment of Carpal Tunnel Syndrome
The purpose of this project is to design and develop a biomechanical manipulation strategy of the carpal tunnel to treat carpal tunnel syndrome.

R01AR068342 (Derwin/Iannotti) 04/01/2016 – 04/16/2021 0.6 calendar
National Institutes of Health / NIAMS $2,471,349 (total direct costs)
Failure with Continuity and Its Relation to Rotator Cuff Repair Clinical Outcomes
This proposal's objective is to challenge and expand our current definition of rotator cuff healing by investigating tendon retraction – broadly defined as medial translation of the repaired tendon away from the bone with or without a defect – as a common and clinically predictive structural outcome following rotator cuff repair. The approach is to characterize tendon retraction using an array of implanted markers, and investigate its relationships to preoperative tissue quality (MRI), post-operative repair integrity (MRI) and clinical outcomes in a prospectively enrolled cohort of 125 patients.

R01EB018965 (Young) 04/01/2016 – 12/31/2019 1.2 calendar
Subcontract from Mayo Clinic (Erdemir)
National Institutes of Health / NIBIB $118,875 (Year 1 total subcontract costs)
Automated Patient Specific Artery Modeling Using Ultrasound Virtual Histology
The goal of this project is to develop tools for patient-specific modeling to facilitate selection of stents for patients with peripheral arterial disease.

What other organizations were involved as partners?

The following organization contributes to the project.

Organization Name: Stanford University
Location of Organization: Stanford, CA
Partner's Contribution to the Project:
In-kind support – Partner provides the SimTK software infrastructure for collaboration and dissemination.
Facilities – Partner provides the SimTK hardware infrastructure for collaboration and dissemination.
Collaboration – Partner develops web based data management and data querying software for the project.

8. SPECIAL REPORTING REQUIREMENTS

COLLABORATIVE AWARDS

Nothing to report.

QUAD CHARTS

An updated Quad Chart can be found in the Appendix.

9. APPENDICES

An updated Quad Chart can be found as an attachment to the Annual Technical Report.

Reference Models for Multi-Layer Tissue Structures

14093001

W81XWH-15-1-0232

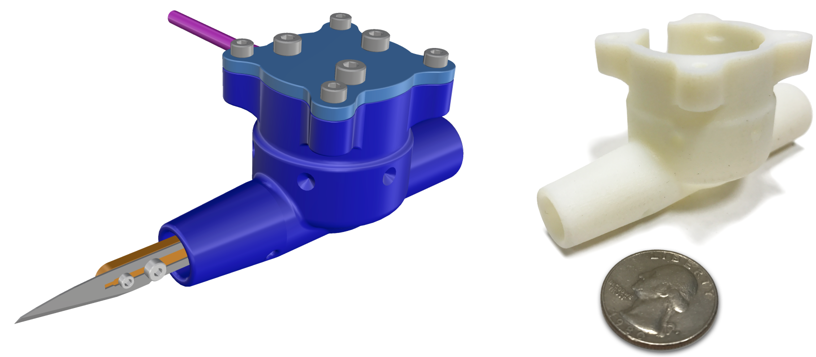
PI: Ahmet Erdemir **Org:** Cleveland Clinic **Award Amount:** ~$3,600,000

Study/Product Aim(s)

- To establish an online platform to curate, distribute, and reuse data and models of multi-layer tissue structures of musculoskeletal extremities.
- To collect and disseminate anatomical and mechanical data for building and validating reference models.
- To build, validate, and disseminate mechanically advanced reference models representative of nonlinear material properties and realistic anatomy.
- To build and evaluate fast and mechanically simplified yet visually and haptically realistic surrogate models to be used for surgical simulation.

Approach

in vivo and in vitro experimentation - nonlinear finite element analysis – surrogate modeling in surgical simulation software - free and open source dissemination



Design work for instrumentation of surgical tools with spatial load transducers has been completed. The design with a surgical blade is shown. Prototype of the housing was manufactured and is illustrated on the left.

Timeline and Cost

Activities	CY	15	16	17	18
Project launch					
Web-based interfaces					
In vivo data collection					
In vitro data collection					
Reference models					
Surrogate models					
Estimated Budget ($K)		**$300**	**$1,200**	**$1,200**	**$900**

Updated: September 30, 2016

Goals/Milestones

CY15 Goal – Project launch

☑ Approval of human subjects testing and cadaver experimentation

☑ Project website

CY16 Goals – Data collection

☐ Web-based interfaces for dissemination – *Testing in progress.*

☐ In vivo anatomy & mechanics – *Data collection in progress.*

CY17 Goal – Data collection & modeling

☐ In vitro anatomy & mechanics, mechanics of surgery – *In progress.*

☐ Reference models from in vivo & in vitro data – *In progress.*

CY18 Goal – Modeling & demonstration

☐ Surrogate modeling – *In progress.*

☐ Demonstration of surrogate models

Comments/Challenges/Issues/Concerns

- Dissemination will be conducted in all years.

Budget Expenditure to Date

Projected Expenditure: $1,200k.

Actual Expenditure: ~$615k.