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Development of a Unique Bioengineering Laboratory Curriculum Focused on Material Characterization of Musculoskeletal Tissues

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Development of a Unique Bioengineering Laboratory Curriculum Focused on Material Characterization of Musculoskeletal Tissues

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Background & Motivation

Bioengineering undergraduate programs feature one or more courses that stress core concepts in Mechanics of Solids and Materials Science so that students are able to understand and characterize the behavior of engineered and biological materials [1]. Ideally, these core concepts are reinforced through hands-on laboratory exercises that investigate the mechanical properties of materials and simultaneously reinforce skills in experimental design, data analysis, and technical communication [2,3]. Ideally, these laboratory experiences involve real-world applications relevant to bioengineering practice, including structure-function relationships, non-linear and time-dependent material responses, and changes in material behavior with injury or disease.

There are several excellent textbooks for both engineering students [5-7] and clinicians in training [7,8] that provide a theoretical foundation for understanding biomaterials; however, there are few resources for instructors who wish to complement these concepts with hands-on biomaterial laboratory experiences [9]. While some institutions develop their own biomaterials labs [2-4], they often face challenges around high set-up and maintenance costs, as well as biosafety concerns when using actual biological tissue samples. There is a need for a biomaterials laboratory curriculum that reinforces core mechanics and materials concepts, highlights the distinctive properties of biomaterials, and addresses the common barriers to real-world lab implementation.

In this paper, we present the development and early implementation of a unique set of laboratory exercises, collectively entitled Musculoskeletal Tissue Characterization (MTC), that involve students performing real-world biomechanical testing protocols to explore structure-function relationships of musculoskeletal tissues. MTC can serve as the core of a stand-alone laboratory course, or it can be used to complement theory-based coursework in bioengineering or biomechanics courses. Individual MTC labs may be offered in any order or combination within these courses; and all conceptual and pedagogical elements can be scaled to both the undergraduate and graduate levels.

In this paper, we will highlight key curricular, pedagogical, and logistical elements of the unique MTC laboratory experiences. To gain formative feedback on lab design and logistics, we conducted structured interviews with faculty likely to adopt MTC labs into their courses and subjected these data to thematic analysis. These results are being used to further refine MTC curriculum, equipment, and lab supplies for a free, open-source launch of the curriculum by

January 2026. More broadly, the work featured in this paper can be used to advocate for the development and implementation of hands-on biomaterials laboratory exercises in engineering programs nationwide.

Musculoskeletal Tissue Characterization (MTC) Laboratory Curriculum

At present, the MTC curriculum consists of three stand-alone laboratory experiences that involve mechanical testing of common musculoskeletal tissues, specifically trabecular bone, tendon, and intervertebral disc. The structure-function and material behavior of these three tissue types are covered extensively in several popular orthopaedic biomechanics textbooks [5-7]. For all MTC labs, students conduct real-world biomechanical testing protocols on surrogate tissue samples. Multiple trials are conducted for each surrogate tissue type in at least two physiologically relevant states, e.g., healthy versus injured tendon, thereby involving concepts like experimental variability and statistical methods for comparison across groups.

Table 1: Learning objectives and curricular elements for MTC laboratory experiences.

MTC Experience	Learning Objectives	Curricular Elements
Bone Density-Dependent Compressive Behavior of Trabecular Bone	• Develop a conceptual understanding of how trabecular bone density affects compressive stiffness and strength • Use experimental data to characterize the mechanical behavior of a linearly elastic biomaterial • Compare the mechanical properties of surrogate versus biological trabecular bone	• Quasi-static, uniaxial compressive testing to failure on surrogate trabecular bone specimens • Multiple test samples of 4 different densities, each intended to correspond to a different human anatomical site or pathological state • Descriptive statistics, nonlinear regression to characterize modulus- and strength-density relationships
Nonlinear Response of Healthy vs. Injured Achilles Tendon	• Develop a conceptual understanding of how tendon microstructure affects whole-tissue mechanical behavior • Characterize the material behavior of a non-linearly elastic biomaterial like tendon via common parameters such as toe region, stiffness, and ultimate force and elongation • Determine how injury (partial tears) affects the mechanical behavior of tendon	• Quasi-static, uniaxial tensile testing to failure on surrogate human Achilles tendon • Multiple test samples of both healthy and injured (partially torn) tendon • Develop an algorithm to consistently and accurately measure mechanical parameters from experimental force-displacement data • Descriptive statistics, one-way ANOVA to compare healthy vs injured tendon
Stress-Relaxation Behavior of Healthy vs. Degenerative Intervertebral Disc	• Develop a conceptual understanding of how anatomical features of intervertebral disc (e.g., nucleus pulposus, annulus fibrosis) interact to create a time-dependent mechanical response under compressive loading • Apply basic viscoelastic theory (standard linear solid) to model the experimental behavior of intervertebral discs under stress relaxation loading conditions • Evaluate the goodness-of-fit of the viscoelastic model and suggest how the accuracy of the model could be improved • Determine how degeneration (annular fissure) affects viscoelastic behavior of intervertebral discs	• Non-destructive, compressive stress-relaxation testing of whole intervertebral disc specimens • Multiple test samples tested intact (healthy) and after manually creating an annular fissure to simulate disc degeneration • Perform nonlinear curve fitting to determine viscoelastic parameters • Descriptive statistics, one-way ANOVA to compare healthy vs degenerated disc

Each of the MTC laboratory experiences consist of three components: (1) an asynchronous orientation module ("pre-lab") that covers the relevant research literature, experimental set-up, and data analysis techniques; (2) an in-person laboratory session (90-120 min) where students collect experimental data and perform preliminary data analyses; and (3) the final deliverable for each lab, which is a structured, long-form conference abstract. For the conference abstract, students must synthesize the relevant research literature, outline their experimental methods, and present key findings in graphical and narrative form. As highlighted in a prior publication by our team [10], we recommend a fading scaffold structure for all conference abstracts, particularly at the undergraduate level. This involves providing students with outlines or partially composed sections of the abstract in early lab experiences and removing these scaffolds in later labs. The pre-lab and conference abstracts are completed individually by each student, and in-lab exercises are intended for small student groups (3-4 individuals).

The MTC laboratory experiences are delivered as free, open-source materials through a commercial learning management system (Canvas LMS). Laboratory exercises are written as stand-alone modules with pre-recorded didactic content, formative assessments, lab protocols, and other student resources. This content may be integrated into an existing course or offered as a stand-alone laboratory course. Each MTC lab takes approximately three weeks to complete with one week for pre- and in-lab completion and two weeks for data analysis and writing the conference abstract. MTC curriculum also includes instructor resources such as rubrics, example student submissions and data sets, and detailed instructor lesson plans.

For each MTC lab, students perform a research-aligned mechanical testing protocols on surrogate orthopaedic tissues. All MTC labs require a uniaxial, materials testing frame with real-time force and displacement read-out (3 kN force and 20 cm displacement required). Institutions may use existing industry-standard test equipment (e.g., MTS or Instron) or purchase the educational-grade test equipment recommended by our team. We recommend table-top mechanical testing frames (Model TSAH by Mark-10, see Figure 1, or Go Direct® Materials Tester by Vernier) that are manually loaded and provide continuous load-displacement read-out. These units are relatively economical (<$5,000 each, including fixtures), which allows institutions to purchase multiple units for a single course. Ideally, every student lab group uses their own test frame.

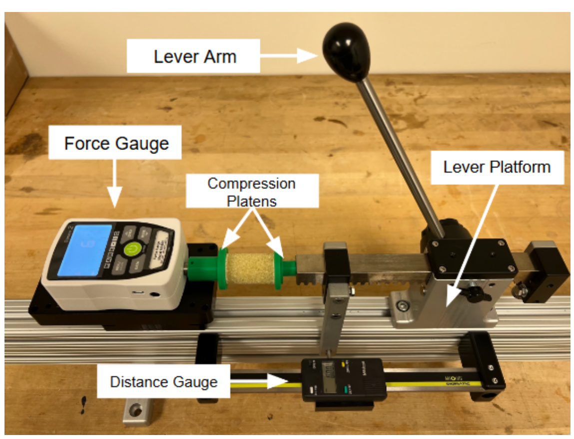


Figure 1: Compression testing of trabecular bone sample on a manually operated, educational-grade table-top test frame (Model TSAH by Mark-10).

MTC laboratory experiences require students to conduct mechanical tests on surrogate musculoskeletal test specimens. Three different specimen types, one for each laboratory experience, were developed by our team in partnership with a leading anatomical model manufacturer (Sawbones®). Each MTC lab requires students to conduct multiple trials (n~5) of every test condition, e.g., healthy and injured tendon; and test specimens cannot be reused due to the destructive nature of the mechanical testing. The cost of these consumable materials was considered when designing surrogate test specimens, with the target being less than $500 per student lab group for all three MTC labs.

Surrogate trabecular bone material has already been developed by our manufacturing partner (Foam Bone Sheets, Sawbones®) for use in orthopaedic implant testing protocols [11]. This trabecular bone surrogate is an open-cell polyurethane foam that is available in various densities (7.5-15 pounds per cubic foot (pcf)) and manufactured in flat sheets. For the MTC curriculum, we created smaller, cylindrical trabecular bone specimens (Figure 2a) with four different densities (7.5, 10, 12, and 15 pcf) that map to human anatomical sites and disease states [11]. These surrogate specimens include solid "cortical bone" endcaps (solid polyurethane foam, 2 mm thickness) to minimize end-artifacts during compression testing. Experimental outcomes for compression tests on first-generation bone samples are presented in Figure 2b.

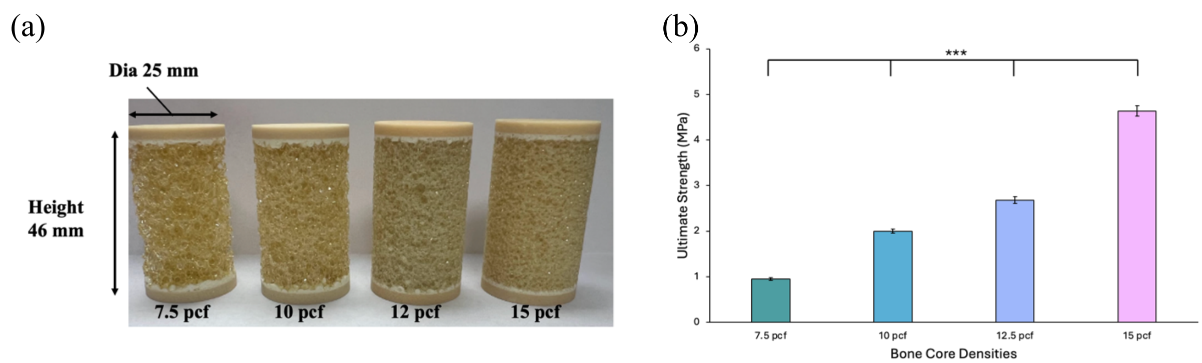
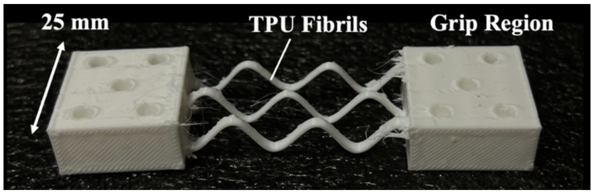


Figure 2: (a) Surrogate trabecular bone compression test specimens of 4 different densities; and (b) example student work presenting compressive strength as a function of surrogate specimen density.

Surrogate tendon specimens were designed specifically for the MTC curriculum. They are a composite of 3D-printed thermoplastic polyurethane (TPU) fibrils embedded in non-structural polystyrene matrix (Figure 3a). The fibrils terminate in rectangular "grip regions" that maximize securement in the custom tension grips. The TPU fibrils have a waveform geometry to mimic the microstructural "crimp" in biological tendon that causes the toe region of the non-linear tension response. The number and continuity of fibrils, their cross-sectional geometry, and their waveform shape can be modified to prescribe toe region, primary and secondary elastic responses, and ultimate (rupture) stress and strain. We are presently calibrating fibril parameters to match physiological behavior for healthy and injured (partially torn) tendon. Test data for first-generation designs are shown in Figure 3b.

(a)



(b)

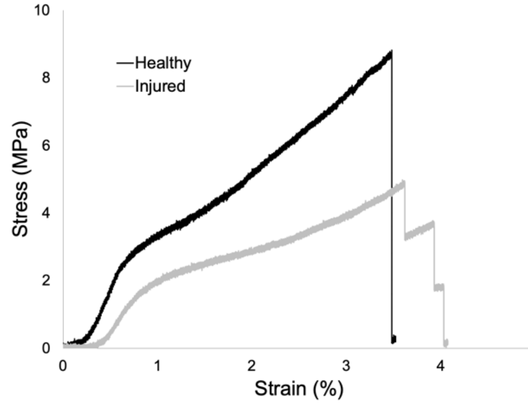
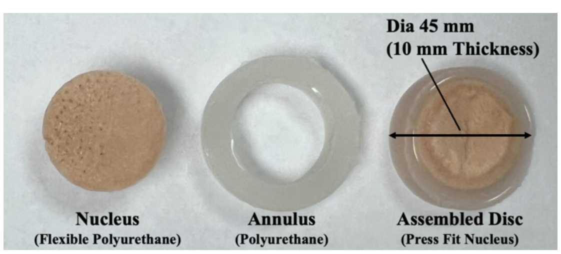


Figure 3: (a) First-generation surrogate Achilles tendon sample shown without polystyrene matrix. Specimen geometry is presently being optimized to better match physiological conditions; (b) Experimental tensile test data showing representative stress-strain responses for first-generation healthy and injured (partially torn) tendon samples.

Intervertebral disc specimens were custom designed for the MTC curriculum (Figure 4a). They consist of a viscoelastic nucleus (flexible polyurethane) encircled by a nonlinearly elastic annulus (polyurethane). Disc injury is simulated by creating an “annular fissure” from the posterolateral surface to the nucleus with a drill bit or punch. First-generation disc samples have a cylindrical geometry, but the next design iteration will be elliptical with a posteriorly offset nucleus to facilitate posterolateral herniation in the injured test condition. This design will also include vertebral endplates (solid polyurethane foam) with perforations in the nucleus region to enhance viscoelastic effects by allowing airflow to/from the nucleus. As seen in Figure 4b, the first-generation design demonstrates a compressive stress-relaxation response that corresponds to a standard linear solid (SLS) viscoelastic model.

(a)



(b)

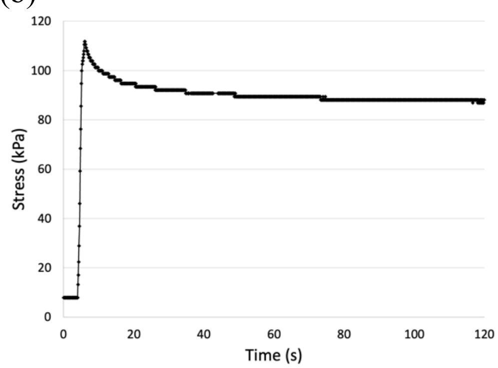


Figure 4: (a) First-generation design for surrogate intervertebral disc. Final design will be elliptical with a posteriorly offset nucleus and also include perforated vertebral endplates; (b) Compressive stress-relaxation response of a healthy first-generation surrogate intervertebral disc specimen.

End-User Feedback on MTC Curriculum

To provide formative feedback on the MTC curriculum design, five (5) engineering faculty were recruited from a single, ABET-accredited, midsized US-based public university. All faculty members had at least 3 years of experience teaching undergraduate (n=3) or graduate (n=3) biomechanics courses in bioengineering (n=3) or mechanical engineering (n=2). Faculty taught either stand-alone lab courses (n=2) or embedded laboratory experiences within their theory-based biomechanics courses (n=3). Lab section sizes were 20-30 students with total enrollment ranging from 50 to 160 students per semester. All faculty self-identified prior to their interviews as potential adopters of MTC labs; and several faculty (n=3) have already used a draft version of the MTC trabecular bone lab.

Structured, voluntary interviews were conducted with each faculty member. Before the start of each interview, the research team gave a brief presentation of the MTC curriculum, allowed subjects to handle samples of the surrogate tissues, and performed a demonstration compression test on a trabecular bone specimen. Study participants were then asked interview questions that focused on the alignment of the MTC labs with their course content, the overall design of the MTC curriculum, and the logistics of implementing MTC in their courses. Participant responses were recorded and subjected to thematic analysis (Table 2).

Table 2: Results from thematic analysis of structured interviews with faculty who self-identified as potential early adopters of the MTC lab curriculum.

Theme	Summary of Findings	Direct Quote(s)
Alignment of MTC labs with course content	• Universal consensus that MTC labs meet the need for hands-on biomechanical testing. • Bone and tendon labs are highly aligned with undergraduate biomechanics courses • Intervertebral disc lab may be beyond undergraduate level if viscoelasticity is not covered. May need to be rescaled.	*Stress relaxation outside the scope of lab. Only cover linearly elastic materials. Tendon lab is good. Bone lab is good.*
Design of MTC curriculum	• Tendon and intervertebral disc surrogate test specimens need to be redesigned to better match test outcomes (e.g., ultimate stress/strain) of biological tissue. • Processing raw mechanical test data seen as valuable skill for students. • Instructors liked being able to use test frame for other experiments. MTC curriculum easy to modify.	*Bones are good. Viscoelastic discs are very nice. Tendons need a little more work. Collagen is prevalent in tendons. Idea to use matrix material to fill up the gap is reasonable and rational. Fine tune design parameters.*
Logistics of implementing MTC curriculum	• No concerns about switching from biological tissue to surrogate specimens. This is seen as a major advantage of the MTC labs. • Table-top test frame is ideal and allows for more hands-on experience than fewer industry-grade frames. • Test frame must be easy to troubleshoot/repair and have user-friendly interface. Liked ability to export data directly to MS Excel. • No concerns about current targets for start-up costs or recurring costs	*Data collection is easier because of one test frame [per group]. Testing will be more efficient since students use the same frame again and again.* *[I] can make lots of arguments for it [MTC Labs] by saying student experience is more valuable and more students can join class now.*

Feedback from the structured interviews suggests that the MTC labs are well aligned with theory-based course content in bioengineering and biomechanics courses. The intervertebral disc stress-relaxation lab may be more suited for graduate students than undergraduates, particularly if viscoelastic constitutive modeling is used for data analysis. Faculty expressed an interest in open-ended design experiences related to orthopaedic interventions, e.g., fracture repair.

In terms of curricular design, faculty liked that the MTC labs require students to analyze raw output data from the mechanical test system and use these data to calculate relevant outcome measures such as modulus of elasticity and ultimate stress. They also liked that the table-top mechanical test frames could be used for lab experiments beyond the MTC curriculum. Several faculty highlighted the tendon and disc surrogate designs should undergo further refinement to better match biological tissue properties.

Lastly, with regards to lab logistics, faculty were not concerned with the initial start-up costs ($5,000 per lab station) nor the recurring costs ($500 per lab group). This is likely because these costs are comparable to instructional budgets for other lab-based courses in engineering programs, e.g., Fluid Mechanics. Faculty liked that all labs used a common mechanical test system but stressed that this equipment must be easy to troubleshoot, repair, and use during lab sessions. The use of surrogate materials instead of biological tissue was seen as a major advantage of the MTC curriculum as it requires fewer consumables, biosafety handling training, and instructor oversight.

Conclusions & Path Forward

This paper introduces a unique set of biomechanics laboratory experiences, entitled Musculoskeletal Tissue Characterization (MTC), that reinforce mechanics concepts in bioengineering and biomechanics. Three lab experiences were developed for the first version of the MTC curriculum, namely: (a) Bone Density-Dependent Compressive Behavior of Trabecular Bone; (b) Nonlinear Response of Healthy vs. Injured Achilles Tendon; and (c) Stress-Relaxation Behavior of Healthy vs. Degenerative Intervertebral Disc. These labs supplement major concepts in popular biomechanics textbooks [5-7], including structure-function relationships for musculoskeletal tissues, linear versus nonlinear deformation, and time-dependent mechanical behavior. In addition, the MTC curriculum is designed to reinforce experimental design, data analysis, and technical communications skills.

Feedback from faculty who are potential early adopters of MTC suggests that this curriculum addresses an existing need for hands-on laboratory experiences related to biomechanics and biomaterials. The MTC labs were perceived to be relevant and well-aligned with course learning objectives, and faculty end-users expressed interest in expanding the lab series to include orthopaedics-centered design experiences. MTC labs were specifically designed to address common obstacles to adopting hands-on biomechanics labs in large-enrollment settings, including high start-up costs and overhead associated with the use of biological tissues. MTC labs use surrogate tissue specimens and economical, table-top mechanical testing platforms.

Ongoing work by our group is focused on curricular refinement and design optimization of lab equipment and test specimens. We will continue to build out student- and instructor-focused materials, including pre-lab exercises, in-lab instructions, example data sets and student work, and detailed rubrics. Based on end-user feedback, we will differentially scale all labs for the undergraduate and graduate levels; and we will rework the intervertebral disc lab in particular to be more relevant to undergraduate courses. We are presently refining the surrogate tendon and intervertebral disc design to better match biological tissues, and our manufacturing partner (Sawbones®) is working on design-for-manufacture of all tissue surrogates. Lastly, our team is engaging with a commercial educational lab equipment manufacturer (Vernier) to manufacture and distribute an economical and user-friendly table-top test frame designed specifically for current and future MTC labs.

In conclusion, the MTC labs presented in this paper address a need for a laboratory curriculum that integrates core bioengineering and biomechanics concepts, highlights the distinctive properties of biomaterials, and addresses the common barriers to real-world lab implementation. We intend to publicly launch the MTC curriculum by January 2026. All curricula will be free and open-source (Canvas LMS), and complete sets of lab equipment and materials will be distributed through reliable manufacturers (Sawbones® and Vernier). We intend for MTC to not only be a valuable resource for the engineering education community but also to serve as a model for other educators to develop and disseminate exiting, hands-on laboratory experiences that complement in-class learning.

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