International Journal of Engineering Education Vol. 34, No. 2(A), pp. 505–513, 2018
Printed in Great Britain

0949-149X/91 $3.00+0.00

A Virtual Biomechanics Laboratory Incorporating Advanced Image Processing and Finite Element Modeling

ANI URAL
Department of Mechanical Engineering, Villanova University, 800 Lancaster Avenue, Villanova, PA 19085, USA.
E-mail: ani.ural@villanova.edu

Biomechanics is an emerging field within mechanical engineering. The number of students who are interested in biomechanics has been increasing in recent years. Therefore, integration of biomechanics concepts into mechanical engineering curriculum is currently of high interest both for students and faculty. This paper outlines a virtual bone testing laboratory that was developed and implemented in a biomechanics course as a part of the graduate mechanical engineering curriculum. Five virtual experiments were designed utilizing advanced image processing and finite element modeling. These experiments incorporated interactive visualization, manipulation, and virtual testing of actual bone images to evaluate the mechanical response of bone. The virtual laboratory created a hands-on learning environment while bridging the gap between theory and real life behavior and helped develop a deep understanding of the underlying fundamental principles of complex mechanics concepts. The assessment of the effectiveness of the virtual experiments through surveys demonstrated an improvement in students' overall understanding of the course material. In summary, the virtual laboratory complemented the theoretical components of the course and created a richer learning environment for the students.

Keywords: virtual laboratory; finite element modeling; biomechanics

1. Introduction

Biomechanics is an emerging field within mechanical engineering. The number of students who are interested in biomechanics has been increasing in recent years. Therefore, integration of biomechanics concepts into mechanical engineering curriculum is currently of high interest both for students and faculty. This paper outlines a virtual bone testing laboratory that was developed and implemented in a biomechanics course as a part of the graduate mechanical engineering curriculum at Villanova University.

The current research on student learning has shown that hands-on learning tools are very effective in improving students' understanding of new concepts [1–4]. This is especially true for complex problems that are difficult to visualize. Students very often struggle to make the transition from abstract concepts to concrete understanding of a subject. Laboratories provide a hands-on experience that reinforces the theoretical concepts introduced in lectures. However, implementation of physical laboratories can present challenges due to high cost and space requirements. Particularly, experiments that may require specialized equipment or material cannot be easily incorporated in a course. In order to remedy these constraints, virtual laboratories have been proposed and utilized in engineering courses in recent years [5].

The application of virtual learning components has been implemented in different forms in engineering courses including recorded experiments, remote access to experimental set ups, and computer simulations of experiments as outlined and reviewed in previous studies [6–18]. One of the powerful computer simulation techniques that simulate physical behavior is finite element modeling. Reinforcement of the concepts covered in lectures with finite element simulations has shown great potential in various engineering courses [12, 19–26]. Several studies have demonstrated that virtual laboratories show similar benefits to physical laboratories and enhance learning [5, 9, 10, 27, 28]. These tools have been mostly utilized in undergraduate courses, however, the implementation of virtual, hands-on components in graduate level courses are also essential to improve the education of graduate students.

In light of the success of hands-on virtual learning components in other disciplines, a virtual laboratory was implemented in the graduate level ME 7550 Biomechanics of Hard Tissues course offered in the Department of Mechanical Engineering at Villanova University. The course targets graduate students as well as high achieving senior undergraduate students and focuses on the mechanical behavior of bone. Typically, similar courses cover only theoretical aspects of bone mechanics and present bone research literature without giving the students an opportunity to have a hands-on experience. Bone, a self-adapting, hierarchical and heterogeneous material, exhibits complex material and mechanical properties. The understanding of mechanical beha-

* Accepted 19 December 2017.

vior of bone is expected to highly benefit from a hands-on laboratory component that provides tools to visualize bone structure and its mechanical response. However, laboratory testing of bone requires dedicated space, equipment, and is costly. As a result, this educational project utilized an innovative approach that incorporated new technologies including high resolution bone imaging, advanced image processing, and finite element modeling to create a virtual laboratory environment. This approach provides a virtual means to test biological materials without the cost and concerns associated with an actual laboratory.

This paper outlines the development and implementation of five biomechanics virtual laboratory modules complementing the theoretical aspects covered in the lectures. In the following sections, the details of the implementation, the learning objectives and the descriptions of the virtual experiments are provided. In addition, the results of the assessment surveys are reported to demonstrate the effectiveness of the virtual laboratory component of the course.

2. Implementation of the virtual biomechanics laboratory

Virtual laboratory component of ME 7550 consisted of five experiments, four of which were in-class exercises and one of the experiments was assigned as a project. The overarching goals of the virtual laboratory modules were (i) improving students' understanding of bone structure and mechanical response by creating a hands-on experience similar to a laboratory setting, (ii) bridging the gap between theory and real life behavior, and (iii) developing a deep knowledge of the underlying fundamental principles of mechanical behavior of bone which serves as a foundation for the understanding of complex mechanics concepts.

The virtual experiments focused on the assessment of material properties and fracture behavior of bone at different scales. They were implemented as a completely hands-on experience in which students visualize bone in three-dimensions, cut out virtual bone specimens, test these specimens under different loading conditions and evaluate their results in class using imaging and finite element modeling software. The virtual experiments were performed individually to improve each student's proficiency in using the software tools that were utilized in the virtual laboratory while enhancing their understanding of bone mechanics. In addition, to facilitate students' learning, two extensive tutorials were prepared providing step by step instructions for the in-class virtual experiments. The tutorials helped students go over any details of the virtual experiments that they may have missed during the class.

The software used in the virtual laboratory included an advanced image processing software ScanIP (Student Edition, Simpleware, Exeter, UK) and the finite element software, ABAQUS (Teaching Edition, version 6.11, Simulia, Providence, RI). Image processing software was used to visualize the bone and cut out bone samples from computed tomography scans of bone. Finite element analysis software was used to simulate mechanical testing conditions by applying loads to the extracted bone sections.

2.1 *Learning objectives of the virtual experiments*

The main goal of the virtual experiments was to give students a hands-on experience that improves their understanding of elastic and fracture behavior of bone at different scales and compartments of bone. The specific learning objectives of the virtual experiments were (i) to develop an understanding of the influence of microarchitecture and microstructure on the apparent elastic properties of trabecular and cortical bone, (ii) to evaluate the fracture processes in bone and their change with age, and (iii) to understand the crack formation and growth at the whole bone level.

In addition to these primary learning objectives, the virtual experiments also supported the improvement of the understanding of continuum mechanics concepts in relation to the mechanical behavior of bone. Furthermore, they provided familiarity with experimental and computational modeling approaches in assessing mechanical behavior of bone. Students were exposed to advanced imaging and finite element software and simulation methods that can be used in solving both biomechanics and other mechanical engineering problems. The virtual experiments replicated the data collection and data analysis components of a physical laboratory through interaction with the finite element simulation software.

2.2 *Description of virtual experiments*

Virtual Experiment 1: Evaluation of the influence of microarchitecture on elastic properties of trabecular bone: The goal of this virtual experiment was to understand the directional dependence of apparent elastic properties of trabecular bone based on its microarchitecture. The module started with three-dimensional visualization of a femur image using the visualization software, ScanIP, and identification of trabecular bone sections in the femur (Fig. 1a). This was followed by extraction of a cubical trabecular bone section from the femur trochanter (Fig. 1b). A finite element mesh of the extracted section was generated within ScanIP. The finite

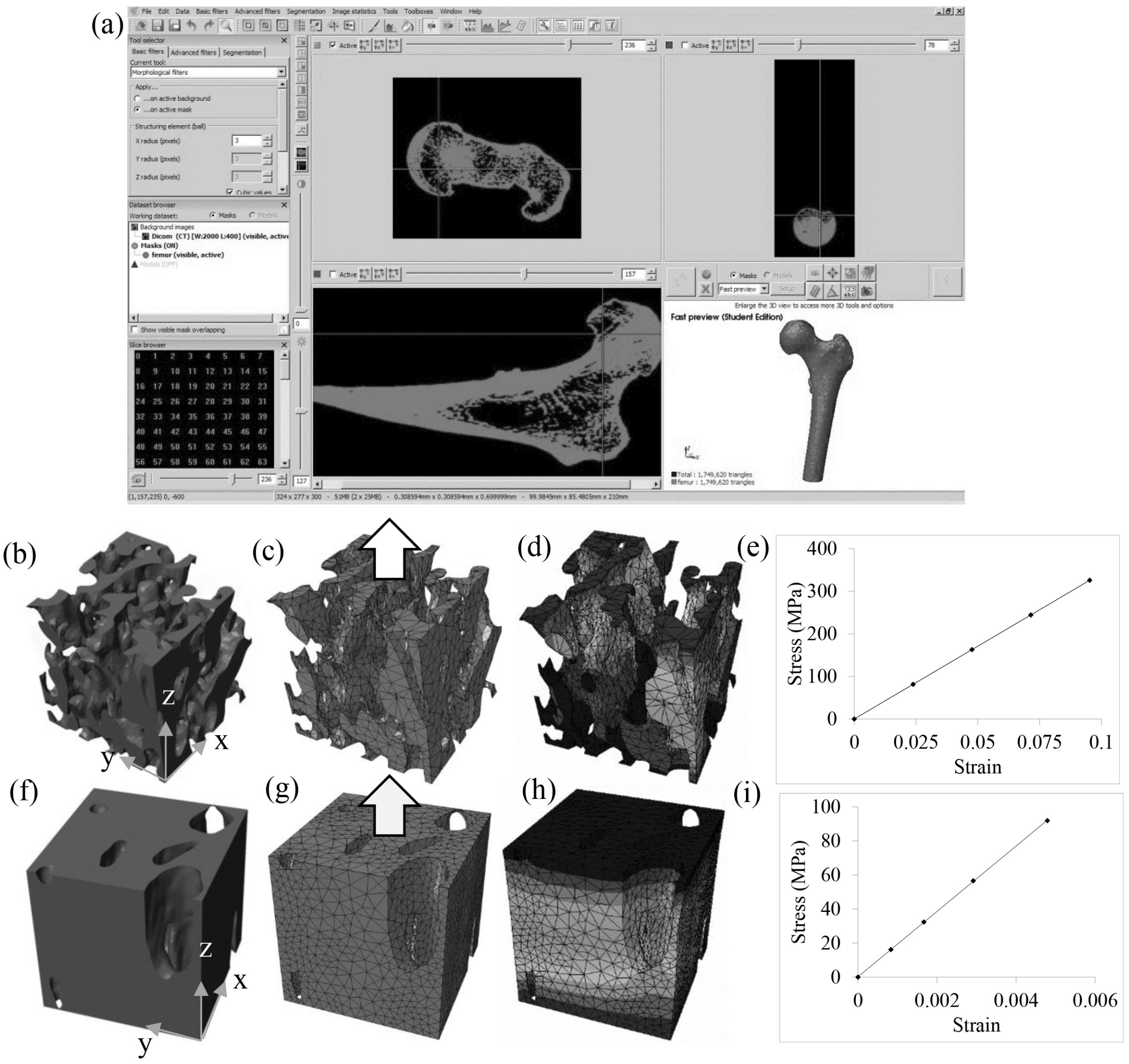


Fig. 1. (a) A screen shot from the imaging software, ScanIP, used in processing the bone images for virtual laboratory testing showing the different compartments of bone. (b) Three-dimensional image of trabecular bone constructed by the imaging software, ScanIP extracted from the femur head region. (c) Finite element meshes of trabecular bone imported into the finite element software, ABAQUS. (d) Displacement contours of the trabecular bone after virtual testing. (e) Stress-strain response of the trabecular model in the z-direction. (f) Three-dimensional image of a sample cortical bone specimen constructed by the imaging software, ScanIP extracted from the femur diaphysis region. (g) Finite element meshes of cortical bone imported into the finite element software, ABAQUS. (h) Displacement contours of the cortical bone after virtual testing. (i) Stress-strain response of the cortical bone model in the z-direction. Note that the white arrows in (c) and (g) denote the loading direction. Note that the opposite surface of the loading was fixed in all directions.

element mesh was imported into the finite element software, ABAQUS (Fig. 1c). The virtual tensile testing of the trabecular bone section in three mutually perpendicular directions was performed in order to assess directional dependence of its apparent elastic properties. Isotropic material properties were assigned to the model based on previous studies reported in the literature [29]. For each simulation the deformed shape of the specimen was analyzed (Fig. 1d) and the results were processed to obtain average stress/strain curves (Fig. 1e). Once the stress-strain curve was obtained the elastic moduli in three mutually perpendicular surfaces were calculated using the slope of the stress-strain curve.

Virtual Experiment 2: Assessment of the influence of bone microstructure on elastic properties of cortical bone: The goal of this virtual experiment was to understand the influence of porosity on the material properties of cortical bone. The module started with three-dimensional visualization of a femur image to identify cortical bone sections in the bone. This was followed by the extraction of three cubical cortical sections from different regions of the femur to obtain bone samples with varying porosity (Fig. 1f). The porosity of each section was evaluated using the visualization software, ScanIP resulting in 3, 8 and 15% porosity. The finite element meshes of the cortical bone sections were generated within ScanIP and were imported into the finite element software, ABAQUS (Fig. 1g). Each cortical bone sample was virtually tested under tensile loading in the longitudinal direction identified during the sample extraction process. All samples were assigned orthotropic material properties based on the values reported in the literature [30]. For all three cortical bone samples, the deformed shape of the specimen was analyzed (Fig. 1h) and the load-displacement curve was extracted. The stress-strain curve and the elastic modulus for each model were determined following the same procedure outlined for Virtual Experiment 1 (Fig. 1i). Finally, the variation of elastic modulus with porosity was plotted.

Virtual Experiment 3: Fracture toughness testing of cortical bone: The goal of this virtual experiment was to visualize and understand the fracture processes in cortical bone and to have a hands-on experience on fracture toughness testing of bone. In this module, the students generated a two-dimensional finite element model of a common fracture toughness testing specimen, compact tension (CT) test specimen (Fig. 2a). The dimensions of the CT specimen were based on tests performed on bone in the literature [31]. The orientation of the CT specimen was such that the crack growth was parallel to the longitudinal direction of the bone. The same set of orthotropic material properties as in Virtual Experiment 2 was utilized in the models. The crack propagation was modeled using extended finite element method (XFEM). This was done by selecting the region around the initial crack as the crack domain. Fracture properties were assigned to this region based on the measured values in the literature [32, 33] defining a linearly degrading cohesive model [31] that represented crack growth parallel to the osteons. The specimen was subjected to displacement control loading. During the virtual test the accumulation of damage and the progression of the crack was observed (Fig. 2b and Fig. 2c). The crack growth amount and load data were extracted from the simulations. Stress intensity factor, which is a measure of fracture toughness, was calculated using the equations reported for CT specimen [34]. The variation of crack length with load and the stress intensity factor with crack extension were plotted.

Virtual Experiment 4: Assessment of femur fracture load: The goal of this virtual experiment was to evaluate the fracture load of whole femur. Following the virtual experiments done on bone sections extracted from the bone, this module focused on the understanding of bone fracture at the macroscale. The module started with processing the image to obtain a three-dimensional view of the femur (Fig. 3a) followed by converting the three-dimensional image to a finite element model (Fig. 3b). The load is applied at a direction that simulates stance loading [35]. The fracture was simulated using XFEM as outlined in Virtual Experiment 3 and the crack domain was selected as the femur neck. For this model, the material properties were assigned as isotropic and the fracture properties were selected based on values reported in the literature [36, 37]. The virtual experiment was performed to observe the damage and crack initiation and propagation under the given loading (Fig. 3c). The load-displacement data was extracted from the simulations to identify the fracture load of the femur that was identified by a sharp drop in the load (Fig. 3d).

Virtual Experiment 5: Assessment of age-related changes in fracture behavior of bone: This experiment was assigned as a project. The goal of the experiment was to understand how changes in material properties of bone affect its fracture behavior. For this virtual experiment, single edge notched bend specimen (SENB) configuration was

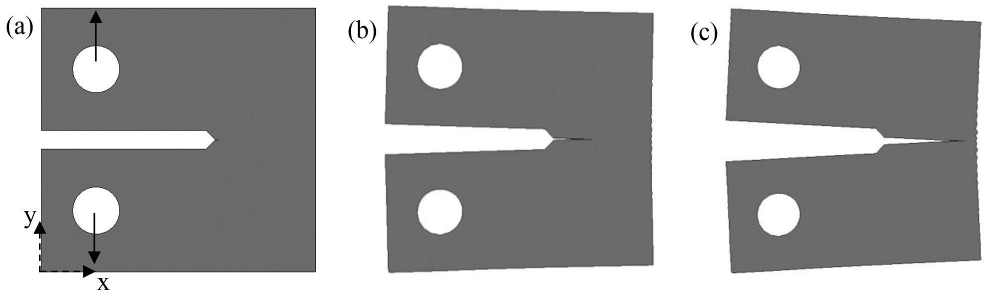


Fig. 2. (a) Finite element model of a compact tension test specimen showing the loading. Note that the specimen was fixed in x direction at the load application point as well as x and y directions on the midpoint of the right edge. (b) Initial stages of crack growth in the specimen. (c) Later stages of crack growth in the specimen.

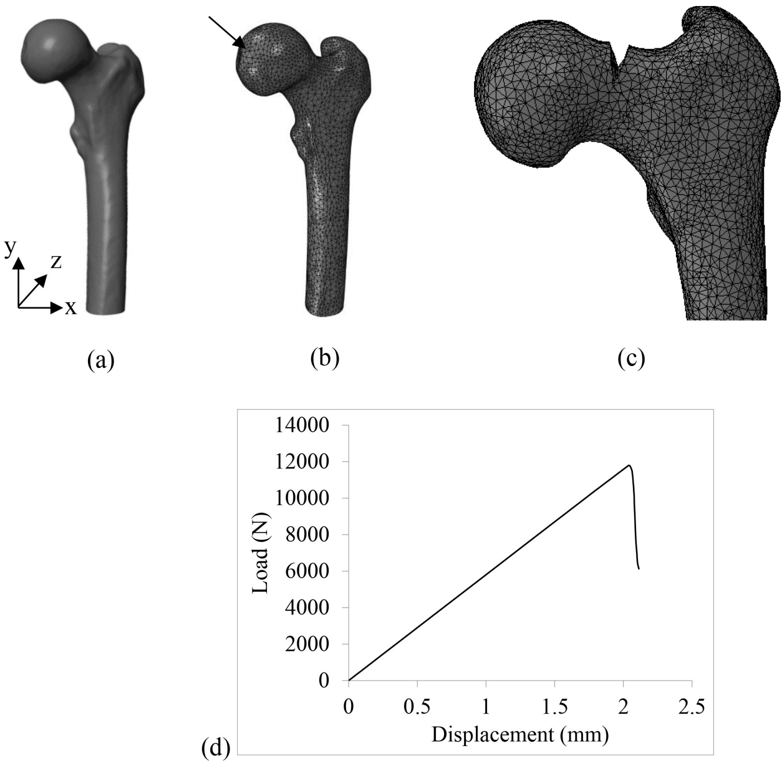


Fig. 3. (a) Three-dimensional model of femur generated in ScanIP. (b) Finite element model of femur that was imported into ABAQUS showing the applied load. Note that the bottom end of the femur was fixed in all directions. (c) Crack growth in femural neck. (d) Load-displacement curve obtained under the femur experiment showing the sharp drop in load identifying the fracture point.

used. The same steps for model generation used in Virtual Experiment 3 were followed. The age-related changes in cortical bone were reflected in the models by varying the fracture properties that were input as a part of the XFEM definition. Three simulations were run on the model with material properties representing 50, 70, and 90 years based on experimental data reported in the literature [36, 37]. This virtual experiment evaluated crack growth perpendicular to the osteons. Therefore, the material properties used in this virtual test differ from the values used in Virtual Experiment 3 which simulate crack growth parallel to the osteons. The crack growth amount and load data were extracted from the simulations and the stress intensity factor was calculated using the equations for SENB specimen [34]. The variation of crack length with load and the stress intensity factor with crack extension were plotted. The deliverables of the project included the simulation results, detailed calculations, and an evaluation of the results in light of the topics covered in class during the semester.

2.3 Results and outcomes of the virtual experiments

The results of the first virtual experiment demonstrated the directional dependence of the elastic properties of trabecular bone. In addition, it showed the difference between the apparent elastic modulus and the material level elastic modulus of trabecular bone which was input into the model. These results helped students gain an understanding of the relationship between microarchitecture and material properties in trabecular bone.

The second virtual experiment showed the reduction in elastic modulus with porosity in cortical bone. It provided direct observation of the influence of porosity on the elastic modulus of cortical bone and contributed to the students' understanding of the influence of microstructure on mechanical properties of cortical bone.

The third and fifth virtual experiments demonstrated the crack growth process in cortical bone and showed how the stress intensity factor increased as the crack propagated. In addition, the results demonstrated the reduction in stress intensity factor with age. By performing these experiments, the students gained an understanding of the fracture toughening processes in bone and the age-related changes in these processes.

The fourth virtual experiment showed how the crack initiated and propagated in femur leading to a sharp drop in the load identifying the fracture point of the bone. During this virtual experiment the students were able to observe how fracture occurred in the femur neck which is one of the most frequent fracture sites observed in real life.

In summary, each virtual experiment provided a hands-on experience in understanding the mechanical response either in a different compartment or at a different length scale of bone. These results supported the theoretical concepts and the review of literature on mechanical behavior of bone covered in class and enhanced the students' understanding of these concepts.

3. Assessment of the effectiveness of the virtual biomechanics laboratory

The effectiveness of the virtual laboratory was assessed through surveys administered before and after the virtual laboratory component of the course. Two surveys were administered during the semester which were structured to measure the influence of virtual laboratory on the students' confidence in their overall understanding of the course material and the value that the students give to the virtual laboratory component of the course. The number of students who completed the surveys was 18.

The first survey was given before the virtual laboratory component and the second survey was given at the end of the semester. The surveys were composed of five to six questions and the first three questions were common in both surveys. Common questions evaluated the students' confidence in their understanding of the new concepts in bone mechanics. The remaining questions were aimed at evaluating the students' perception of the additional contribution of virtual laboratory to their learning. The students were given a scale ranging between 1 to 5 (1 = I do not understand it, 5 = I fully understand it for questions 1 to 3, 1- I do not visualize/understand it, 5=I fully visualize/understand it for question 4 and 1 = I do not agree, 5 = I agree for questions 5 and 6). The survey questions are outlined in Table 1.

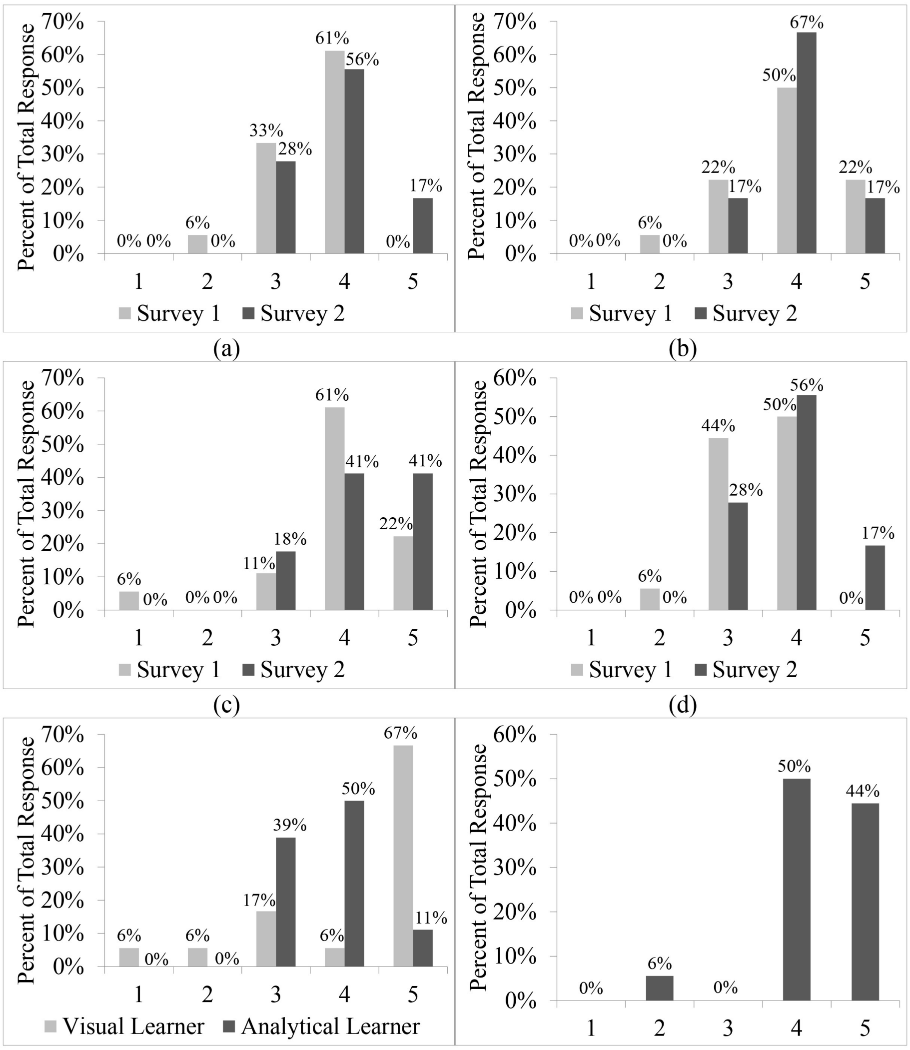
The results of the surveys showed that the virtual laboratory had a positive effect on students' confidence in their understanding of bone mechanics concepts (Fig. 4). Questions 1 to 3 were the same in both surveys and directly assessed the students' general understanding of the material covered in the class. Since Survey 1 and Survey 2 were given before and after the virtual laboratory component of the course the difference in the survey responses were expected to reflect the contribution of the virtual laboratory in students' learning. For all three questions, there was a 10% increase in the total number of students who selected 4 and 5 which represents a good understanding of the material covered in class (Fig. 4a–4c). In addition, although there were not any students who selected 5 for Question 2 and 3 in Survey 1, after the virtual laboratory component was covered 17% of the students shifted to the highest learning group (Fig. 4a–4c). The students who were in the below average learning level increased their learning to average or high levels. These results show that the virtual laboratory improved the learning experience of all students by shifting the lowest groups to higher levels and moderate understanding group to the highest group.

The assessment of the visualization of the bone behavior response (Question 4) before and after the virtual laboratory showed similar trends to Questions 1 to 3 (Fig. 4d). There was a 20% increase in the highest learning group after the virtual laboratory indicating that hands-on experience in the course improved the understanding and visualization of bone behavior. In addition, below average group increased their learning to moderate and high levels leaving no students in the below average group.

Another component of the survey was to assess the visual and analytical learner groups. Vast majority of the students (73%) identified themselves as visual learners (Fig. 4e). However, the data also showed that most of the students see themselves

Table 1. List of Survey 1 and Survey 2 questions. Note that first three questions are the same in both surveys and the remaining questions are specific to each survey

Survey 1 Questions	**Survey 2 Questions**
1. How do you rate your understanding of bone structure?	**1.** How do you rate your understanding of bone structure?
2. How do you rate your understanding of elastic behavior of bone?	**2.** How do you rate your understanding of elastic behavior of bone?
3. How do you rate your understanding of fracture behavior of bone?	**3.** How do you rate your understanding of fracture behavior of bone?
4. I can visualize the experiments (how bone deforms, how a crack grows in bone) that relate to bone mechanics and fracture based on the images provided in class.	**4.** Virtual laboratory exercises helped me visualize the experiments (how bone deforms, how a crack grows in bone) that relate to bone mechanics and fracture.
5. I am a visual learner who understands concepts through hands-on exercises.	**5.** Combined lecture and finite element modeling approach allowed me to understand bone mechanics better.
6. I am an analytical learner who understands concepts based on theory and reading.	



(a) (b)

(c) (d)

(e) (f)

Fig. 4. Comparison of student responses between Survey 1 and Survey 2 for (a) Question 1, (b) Question 2, (c) Question 3, (d) Question 4 (e) Comparison of student responses between Question 5 from Survey 1 and Question 6 from Survey 2 (f) Student responses to Question 5 in Survey 2. Note that the students were given a scale ranging between 1 and 5: For Questions 1–3: 1 = I do not understand it, 5 = I fully understand it; For Question 4: 1 = I do not visualize/understand it, 5 = I fully visualize/understand it; For Questions 5–6: 1 = I do not agree, 5 = I agree.

both as analytical and visual learners (61%). This indicates that combining hands-on activities with theoretical concepts may work the best to improve students' learning. This is also supported by the response of students to Question 5 in Survey 2. Almost all students (94%) agreed that the combined approach allowed them to learn the course material better (Fig. 4f). This outcome supports the development of the virtual laboratory in ME 7550 to improve students' understanding of the theoretical components of the course.

4. Discussion

The assessment outcomes showed that the virtual laboratory component improved the students' confidence in their overall understanding of the course material. In addition, it complemented the theoretical components of the course and created a richer learning environment for the students. The positive response of the students to the virtual laboratory highlights the importance of implementation of hands-on learning tools in engineering courses. Another important outcome of the assessment was the high percentage of students that were both analytical and visual learners. This underlines the importance of structuring the courses to serve this combined learning approach. The students may get the most benefit from presentation of the theory of a subject followed by hands-on activities as outlined in this study.

The main limitation of the study is that the assessment was only based on the students' perception of the effectiveness of the virtual laboratories. This course was developed with the virtual laboratory component from the first time it was taught. Therefore, there was no data available to compare the students' performances with or without the virtual laboratories. Another limitation of the study is the relatively limited sample size of the students that completed the surveys. The enrollment to the course was not very high due to the elective graduate level nature of the course.

5. Conclusions

This paper demonstrated an effective implementation of advanced engineering software in a biomechanics graduate course to create a virtual laboratory that provides a hands-on experience in visualization and testing of bone. The current project serves as a case study for implementing virtual laboratory teaching approach to improve learning and teaching processes in engineering. Based on the positive outcomes of the project, this approach can be applied to other mechanical engineering courses that could benefit from a laboratory component which requires extensive resources to implement physically.

Acknowledgements—This project was supported by Villanova Institute for Teaching and Learning.

References

1. L. E. Carlson and J. F. Sullivan, Hands-on engineering: learning by doing in the integrated teaching and learning program, *International Journal of Engineering Education*, **15**(1), 1999, pp. 20–31.
2. H. A. Hadim and S. K. Esche, Enhancing the engineering curriculum through project-based learning, *IEEE Frontiers in Education*, Boston, MA, 2002.
3. D. W. Knight, L. E. Carlson and J. F. Sullivan, Improving engineering student retention through hands-on, team based, first-year design projects, *Proceedings of the International Conference on Research in Engineering Education*, Honolulu, HI, 2007.
4. R. N. Savage, J. Stolk and L. Vanasupa, Collaborative design of project-based learning courses: How to implement a mode of learning that effectively builds skills for the global engineer, *Proceedings of the American Society for Engineering Education Annual Conference*, Honolulu, HI, 2007.
5. T. De Jong, M. C. Linn and Z. C. Zacharia, Physical and virtual laboratories in science and engineering education, *Science*, **340**(6130), 2013, pp. 305–308.
6. S. Ayatollahi, S. M. Tauseef, C. Guzman and S. Mohebinia, Development of a user-friendly virtual laboratory for simulating three-dimensional transient heat transfer in regularly shaped solids, *International Journal of Mechanical Engineering Education*, **36**(1), 2008, pp. 81–89.
7. B. Balamuralithara and P. C. Woods, Virtual laboratories in engineering education: The simulation lab and remote lab, *Computer Applications in Engineering Education*, **17**(1), 2009, pp. 108–118.
8. P. Bhargava, J. Antonakakis, C. Cunningham and A.T. Zehnder, Web-based virtual torsion laboratory, *Computer Applications in Engineering Education*, **14**(1), 2006, pp. 1–8.
9. J. R. Brinson, Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research, *Computers & Education*, **87**, 2015, pp. 218–237.
10. J. Ma and J. V. Nickerson, Hands-on, simulated, and remote laboratories: A comparative literature review, *ACM Computing Surveys (CSUR)*, **38**(3), 2006, p. 7.
11. V. S. Pantelidis, Virtual reality and engineering education, *Computer Applications in Engineering Education*, **5**(1), 1997, pp. 3–12.
12. S. Shakerin and D. D. Jensen, Enhancement of mechanics education by means of photoelasticity and finite element method, *International Journal of Mechanical Engineering Education*, **29**(4), 2001, pp. 307–320.
13. H. Lee, An example of the interaction between virtual and physical experiments in dynamics, *International Journal of Mechanical Engineering Education*, **32**(2), 2004, pp. 93–99.
14. C. Peek, O. Crisalle, S. Depraz and D. Gillet, The virtual control laboratory paradigm: Architectural design requirements and realization through a DC-motor example, *International Journal of Engineering Education*, **21**(6), 2005, pp. 1134–1147.
15. A. Sampaio, D. Rosario, A. Gomes and J. Santos, Virtual reality applied on civil engineering education: Construction activity supported on interactive models, *International Journal of Engineering Education*, **29**(6), 2013, pp. 1331–1347.
16. F. Torres, F. A. Candelas-Herías, S. T. Puente Méndez, J. Pomares, P. Gil and F. G. Ortiz Zamora, Experiences with virtual environment and remote laboratory for teaching and learning robotics at the University of Alicante, *International Journal of Engineering Education*, **22**(4), 2006, pp. 766–776.
17. H.-P. Yueh and H.-J. Sheen, Developing experiential learning with a cohort-blended laboratory training in nano-bio engineering education, *International Journal of Engineering Education*, **25**(4), 2009, p. 712.
18. H. Zhou, Z. Lei, W. Hu, Q. Deng, D. Zhou and Z.-W. Liu, A Multi-criteria Method for Improving the Assessment of Students' Laboratory Work Using Online Laboratory, *International Journal of Engineering Education*, **33**(5), 2017, pp. 1654–1663.
19. L. C. Brinson, T. Belytschko, B. Moran and T. Black, Design and computational methods in basic mechanics courses, *Journal of Engineering Education*, **86**(2), 1997, pp. 159–166.
20. W. E. Howard, J. C. Musto and V. Prantil, Finite element analysis in a mechanics course sequence, *Proceedings of the American Society for Engineering Education Annual Conferenace and Exposition*, Albuquerque, NM, 2001.
21. H. Jenkins and J. Mahaney, Improving mechanical design education using solid modeling and finite element analysis modules, *Proceedings of the ASEE Southeast Section Annual Conference*, Chattanooga, TN, 2005.
22. H. F. Lam, S. Kitipornchai and T. Reichl, Development of a virtual testing application for the teaching and learning of structural engineering, *The IES Journal Part A: Civil & Structural Engineering*, **3**(2), 2010, pp. 119–130.
23. C. Lissenden, G. Wagle and N. Salamon, Applications of finite element analysis for undergraduates, *Proceedings of the American Society for Engineering Education Annual Conference and Exposition*, Montreal, Canada, 2002.
24. A. Ural, A hands-on finite element modeling experience in a multidisciplinary project-based freshman course, *Computer Applications in Engineering Education*, **21**(2), 2013, pp. 294–299.
25. A. Ural, J.R. Yost, D. W. Dinehart, and S. P. Gross, An Integrated Freshman Project Course Combining Finite Element Modeling, Engineering Analysis and Experimental Investigation, *Proceedings of the American Society for Engineering Education Annual Conference and Exposition*, Vancouver, Canada, 2011.
26. B. Young, E. Ellobody and T. W. C. Hu, 3D Visualization of Structures Using Finite-Element Analysis in Teaching, *Journal of Professional Issues in Engineering Education & Practice*, **138**(2), 2012, pp. 131–138.
27. S. P. Brophy, A. J. Magana and A. Strachan, Lectures and Simulation Laboratories to Improve Learners' Conceptual Understanding, *Advances in Engineering Education*, **3**(3), 2013, pp. 1–27.

28. T. Wolf, Assessing student learning in a virtual laboratory environment, *IEEE Transactions on Education*, **53**(2), 2010, pp. 216–222.
29. X. S. Liu, X. H. Zhang, K. K. Sekhon, M. F. Adams, D. J. McMahon, J. P. Bilezikian, E. Shane and X. E. Guo, High-resolution peripheral quantitative computed tomography can assess microstructural and mechanical properties of human distal tibial bone, *Journal of Bone and Mineral Research*, **25**(4), 2010, pp. 746–756.
30. R. B. Ashman, S. C. Cowin, W. C. Van Buskirk and J. C. Rice, A continuous wave technique for the measurement of the elastic properties of cortical bone, *Journal of Biomechanics*, **17**(5), 1984, pp. 349–361.
31. A. Ural and D. Vashishth, Cohesive finite element modeling of age-related toughness loss in human cortical bone, *Journal of Biomechanics*, **39**(16), 2006, pp. 2974–2982.
32. H. Cezayirlioglu, E. Bahniuk, D. T. Davy and K. G. Heiple, Anisotropic yield behavior of bone under combined axial force and torque, *Journal of Biomechanics*, **18**(1), 1985, pp. 61–69.
33. D. T. Reilly and A. H. Burstein, The elastic and ultimate properties of compact bone tissue, *Journal of Biomechanics*, **8**(6), 1975, pp. 393–405.
34. ASTM E399, ASTM Standard E399 Standard Test Method for Linear-Elastic Plane-Strain Fracture Toughness KIc of Metallic Materials. 2012.
35. A. A. Ali, L. Cristofolini, E. Schileo, H. Hu, F. Taddei, R. H. Kim, P. J. Rullkoetter and P. J. Laz, Specimen-specific modeling of hip fracture pattern and repair, *Journal of Biomechanics*, **47**(2), 2014, pp. 536–43.
36. R. W. McCalden, J. A. McGeough, M. B. Barker and C. M. Court-Brown, Age-related changes in the tensile properties of cortical bone. The relative importance of changes in porosity, mineralization, and microstructure, *Journal of Bone and Joint Surgery American*, **75**(8), 1993, pp. 1193–1205.
37. P. Zioupos and J. D. Currey, Changes in the stiffness, strength, and toughness of human cortical bone with age, *Bone*, **22**(1), 1998, pp. 57–66.

Ani Ural is an Associate Professor in the Department of Mechanical Engineering at Villanova University. She obtained her MS and PhD degrees from Cornell University. She also held a postdoctoral research associate position at Rensselaer Polytechnic Institute in the Department of Biomedical Engineering before she joined Villanova University in 2007. Her research interests include computational biomechanics, fracture mechanics, and solid mechanics. She is funded by National Science Foundation.