

Virtual Musculoskeletal Scenario-Testing Case-Studies

Madusudanan Sathia Narayanan, Srikanth Kannan, Leng-Feng Lee, *Student Member, IEEE*,
Frank Mendel and Venkat N. Krovi, *Member, IEEE*

Abstract—Doctors, dentists, nurses, athletic trainers, occupational therapists and allied health-care professionals are expected to learn the linkage between anatomy, physiology and ultimately functional-performance of muscles i.e. how muscles affect movement or which sets of muscles carry various loads. However the extent of understanding of functional-performance that can be imparted in a didactic-lecture or cadaver-lab setting of a “Gross Anatomy” class is limited. Hence we seek to create the architecture and algorithms for scaffolded interaction with human musculoskeletal simulation models (virtual prototypes) that can make varied “what-if” type analyses and hypothesis-testing possible. This is very pertinent in the context of the target audience of healthcare professionals who may lack prior exposure to such virtual computational scenario testing tools. Providing such access is vital to training of the next generation of health care professionals to leverage ubiquitous computing and the quantitative-paradigm.

I. INTRODUCTION

DOCTORS, dentists, nurses, athletic trainers, physical therapists are expected to learn musculoskeletal anatomy (and to varying degrees about muscle physiology). However the ultimate goal of such training is to gain an understanding of muscle functional performance – to understand how muscles affect movement or which sets of muscles carry the load. Since most outcomes are realized by co-activation of multiple muscles, it is difficult for students to convert structural knowledge of muscle-attachments to a functional understanding of movement and load-bearing capacity.

Traditionally, in the health-sciences arena, the concepts of musculoskeletal anatomy are delivered in a classroom-based lecture followed by a stint in a cadaver lab. Current instructional modes discuss individual muscles and their attachments and provide tables or charts indicating which muscles power various movements. While students are able to visualize anatomical concepts, such as origin and

insertion of individual muscles and their lines of action, system-level notions of motions and forces are difficult to demonstrate and comprehend. This includes both studying the concerted action of multiple muscles, as well as isolating the contribution of individual muscles. Further, the lack of interactivity precludes the capacity to create “what-if” scenarios’, e.g., what happens if muscle A is lost or provides only half of normal force in order to develop intuition about cause and effect.

In recent years, the growth of various bioengineering programs has brought about a greater emphasis on the quantitative study of musculoskeletal systems. Motions and forces in such systems may be determined by solving the redundant differential-algebraic governing-equations together with additional optimization criteria. Although mathematical formulation can now be emphasized, the problem complexity restricts deployment to very simple musculoskeletal subsystems with a few joints/muscles and relatively simple geometries.

The concurrent development of professional-grade, commercial [1, 2], and open source [3, 4] musculoskeletal analysis tools facilitates creation and computational analysis of biomechanically-accurate models. Constrained-musculoskeletal-system models can be constructed modularly by placing physiologic and behavioral constraints on anatomical components. Analyses range from simple collision detection, muscle routings to increasingly complex physical (motions and forces) or physiological (muscle activity, tendon length etc.) investigations. The resulting responses can now be visualized in a 3D interactive graphical virtual environment. A wide variety of test suites can be repeatedly run on such virtual computer models while involving users of all stripes without the usual limitations of time, space or cost.

Thus, the prospect of teaching the linkage between form and function using “virtual models” and “virtual experimentation” is now within the realm of possibility. The benefits of this method are that the students can analyze more complex bodies with detailed muscular geometries and complex joints; obtain quick results; conduct comparison studies using different parametric models, aided by the detailed visualization of virtual models. This gives the student a better functional understanding of the musculoskeletal systems and the functionality of the overall system. Considerable confidence may be placed in the results since the virtual musculoskeletal analysis tools are developed on the basis of algorithmic implementation of

Manuscript received April 7, 2008. This work was supported in part by The Research Foundation of State University of New York and National Science Foundation CAREER Award (IIS-0347653).

V. N. Krovi (e-mail: vkrovi@buffalo.edu) is an Associate Professor, M. S. Narayanan (e-mail: ms329@buffalo.edu), S. Kannan (e-mail: ks269@buffalo.edu) are M.S. students and L-F. Lee (e-mail: llee3@buffalo.edu) is a Ph.D. student – all with the Mechanical & Aerospace Engineering Department, State University of New York at Buffalo, Buffalo, NY 14260 USA. URL: mechatronics.eng.buffalo.edu (phone: 716-645-2593 Ext. 2264; fax: 716-645-3875).

F. Mendel (e-mail: fcmendel@buffalo.edu) is an Associate Professor with the Pathology and Anatomical Science Department, the State University of New York at Buffalo, Buffalo, NY 14260 USA.

analytic formulations. However, the principal limiting factor is the complexity of the underlying computational tools, which pose special pedagogic challenges.

Hence, we seek to create a set of high fidelity Virtual Musculoskeletal Model coupled with a Scaffolded Learning Framework to serve as a mechanism for performing preparatory exercises as well as to improve overall understanding of “Gross Anatomy” concepts. Our Virtual Musculoskeletal Model are intended to provide students with opportunities to experiment with and interactively learn course material in “Gross Anatomy” through structured exercises with virtual simulation based models. The emphasis is on providing a structured framework to facilitate this learning process while enabling the student to examine and practice at leisure. The resulting framework would be of great interest in teaching a spectrum of end users – from the health care students to clinicians pursuing Continuing Medical Education (CME) credits to real world practitioners from many perspectives:

- Learning Anatomy: Interactive Virtual Musculoskeletal system analyses to quantitatively analyze muscle activations to effect particular motions could greatly improve student comprehension and refocus attention on function rather than on vocabulary and relationships.
- Applying Anatomy: Interactive Virtual Musculoskeletal system analyses (that allow clinicians to selectively “take out” muscles or parts of muscles and observe the effects on movement) could serve as invaluable teaching and diagnostic tools.

Our ultimate goal is to create this framework to supplement both the traditional lecture based classroom and the limited lab access to cadaver dissection tables for these large classes.

The rest of the paper is organized as follows: Section II presents brief overview of Virtual Prototyping/ Simulation Based Design and comparison between conventional and virtual prototyping approaches in musculoskeletal paradigm followed by pedagogical issues in Section III. Implementation of Virtual Musculoskeletal Model Framework is presented in Section IV while the results of the two case studies using our framework are discussed in Section V. Finally, Section VI concludes the paper.

II. VIRTUAL PROTOTYPING / SIMULATION BASED DESIGN

Figure 1(a) and (b) compares the conventional and virtual prototyping approaches for musculoskeletal analysis highlighting the fact that conducting such analysis on real biological specimens (cadavers) may not be possible or can be expensive and time consuming. Such use of integrated virtual analysis tools/environments facilitates detailed studies to be performed at the convenience of the user. The adoption of a computational-analysis paradigm is beneficial from the viewpoint of helping with improved quantitative conceptualization and understanding of the anatomical system and its behavior [5].

In such a setting, a series of simulation based–studies can be developed in the form of “what– if” type problems with a clear emphasis on systematic generation, evaluation and elimination of choices. Simulation Based Design (SBD) tools in engineering have capitalized on setting-up and solving such analytic problems by coupling parametric models with functional simulation tools and optimization methods [6, 7]. Two trends that have favored the adoption and rapid proliferation of the simulation based approach are:

- (i) The availability of low-cost PC based parametric simulation and analysis tools; and
- (ii) The capability of integrating multiple functionalities into a unified environment.

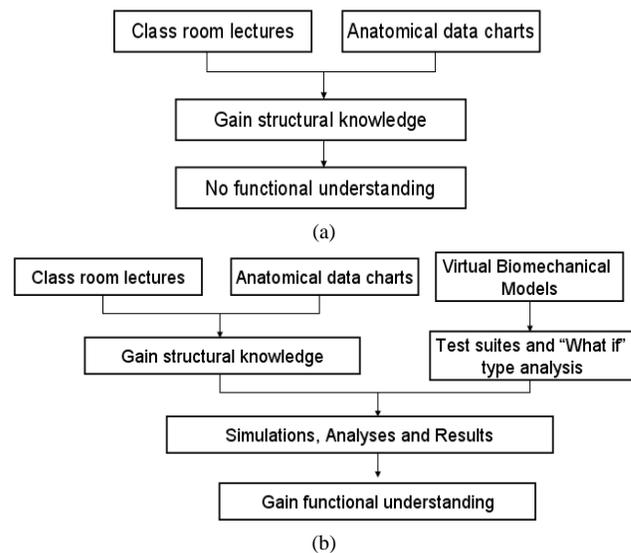


Fig. 1: (a) Conventional Teaching Approach; (b) Virtual Prototyping Approach.

Today, computer simulation may be used to compute and calculate the kinematic, dynamic and finite element analysis based on responses of virtual systems completely within the computer and the result can be visualized within a 3D interactive virtual environment. Further, the ubiquitous availability of low-cost personal computer processors with accelerated graphics hardware coupled with the ease of availability of the tools for such platform has set the stage for this new phase in engineering, enhancing the user’s capability to comprehend the complete behavior of the system and relations between different states of a system. The trend of integrating different modules and packages has permitted users not only to create virtual 3D models of interest, but also to analyze the system by functional simulation within the virtual environment and ultimately to study a complex system based on its response.

The ability to perform functional evaluations depends on the availability of functional simulation tools. However, the effectiveness of those is limited by the extent of capture of the underlying physics, the modeling and analysis fidelities and ultimately computational power. In developing tutorial case studies for our application, the effective simulation of musculoskeletal performances becomes critical. Varying

levels of such simulations are possible – e.g. several digital-human modeling tools such as Jack allowed kinematic modeling of human device- environment interactions. The ability to monitor internal human variables, such as joint angles and torques, from the virtual avatar formed the basis of a user-customized development of human-worn products [8, 9]. In recent times, a number of computational musculoskeletal-analysis tools such as SIMM [1, 10] or AnyBody [11], or the even more recent OpenSim [3, 4] framework has become available.

III. PEDAGOGICAL ISSUES

In recent times interactive technological tools have tremendous potential to address a broad range of educational objectives from presentation (providing information), exploration (explore alternative choices). However, the lack of room in the traditional undergraduate anatomy curriculum coupled with the lack of an audience-specific structured learning frameworks have posed barriers. Several innovative solutions, in the form of “virtual labs” that leverage the ongoing revolutions in computing and communication infrastructures, have been considered in the engineering domain. Virtual access labs and asynchronous experiments have focused on providing remote web-based access to restricted resources such as hydraulics experiments [12] or robotic arms [13, 14]. Other virtual labs take the form of supplementary interactive educational technology modules/ curricula that provide enhanced audio-visual interactivity, e.g., increased immersion within 3D VRML based worlds [15]. Such efforts have had tremendous success in addressing a broad range of educational objectives [16]; accommodating different learning styles [13] and students from diverse educational backgrounds [17, 18]; and in serving as modular mechanisms for dissemination [18]. However, the true power of such virtual labs comes to the forefront as one begins to parametrically interact, simulate and explore the virtual model space, thus developing a more intuitive understanding of the underlying concepts in general. From this viewpoint, the musculoskeletal anatomy literature has many examples of approaches incorporating parametric interactivity in a research setting. We leverage a similar parametric interactivity in implementing our musculoskeletal tutorials.

While there are undoubtedly tremendous benefits to be derived in terms of enhanced productivity, there are also numerous issues surrounding the successful use of these new and sophisticated tools. Traditionally, many levels of “scaffolding” are usually required in training of users – wherein an expert in the field helps a novice learner succeed in complex tasks that would otherwise be beyond his/her reach. The two critical desired features of such a learning framework are:

- (a) Learners receive varying levels of task- and context-dependent assistance
- (b) Learners draw from that experience and improve in

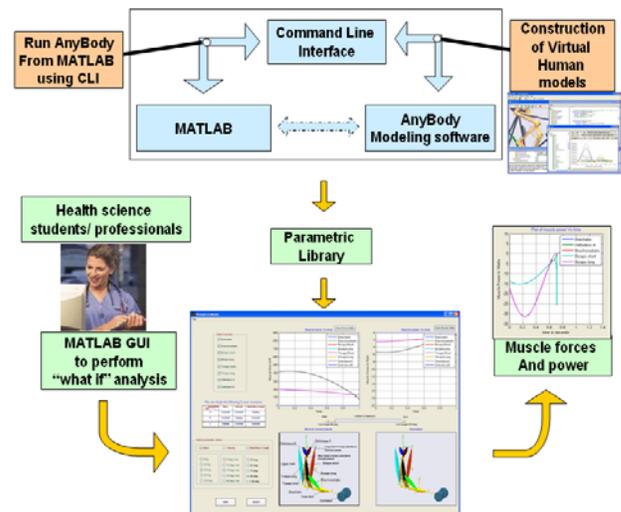


Fig. 2: Virtual Musculoskeletal Model Framework.

process, skills and/or content understanding.

However, the development of a systematic mechanism for capture and subsequent transfer of experience and skills has proved to be difficult despite the availability and use of immersive and interactive multimedia software principally due to the lack of structured frameworks.

It is to address this shortfall that we developed these virtual anatomical tutorial case-studies for a target audience of students in a senior-level “Gross Anatomy” course as well as other health practitioners. These case-studies help in clear understanding of functional relationship of muscles under different “what-if” scenarios. In addition, we also incorporated erroneous (but “intuitive”) directives at several places within the tutorials. Ultimately, the principal desired outcome of these tutorials is to promote the development of cognitive inquiry within the student and accelerating their learning experience without increasing the lecture hours. At the same time the created framework also helps us address the more immediate goals of reinforcement of concepts being presented in the course by paralleling the course material in the case-studies.

IV. IMPLEMENTATION

Figure 2 presents the high level overview of the architecture of the Virtual Musculoskeletal Model Framework designed to help health science professionals interact with and study functional performance aspects of the human musculoskeletal system. The intent is to provide structured access to these musculoskeletal models, run the various analyses and returns the results back in the timely manner within a user-friendly interface. The three key contributors of this process are: (i) Computational Musculoskeletal Analysis Tools (ii) Scaffolded Graphical User Interface and (iii) Quantitative Performance Measures.

A. Computational Musculoskeletal Analysis Tools

Musculoskeletal systems consist of numerous bones connected together at joints, activated by muscles and thus

can be treated within framework of Articulated Multi-Body Systems (AMBS) [19]. Unlike traditional engineering systems, musculoskeletal systems inherently possess considerable redundancies, which can be resolved typically leveraging an optimization approach. Several commercial packages are available to implement the specialized forward/inverse dynamics of the musculoskeletal system [11, 19, 20].

Among these, the AnyBody Modeling System is a convenient tool for analysis of the musculoskeletal system of vertebrates that we adopt. Constrained musculoskeletal system-level computational models will be constructed modularly using the AnyBody software package by placing physiologic and behavioral constraints on anatomical components (e.g., bone, muscle, and tendon). A variety of qualitative and biologically relevant data such as muscle forces, joint reactions, metabolism, mechanical work, efficiency, etc. can be easily accessed for subsequent analyses.

The parametric nature of the AnyBody software package permits the use to change many aspects of the virtual model prior to running the inverse dynamics analysis. These include the biological muscle parameters (such as types of muscles, pennation angle), effective mechanical properties (such as stiffness, strength, muscle-tendon length) and geometric properties (such as origin/insertion points and lines of flexion of muscles). However, as we noted earlier this can be realized only by tedious scripting process using AnyScript that (i) requires specialized programming knowledge and (ii) prone to error. The automation of many facets of this process (using MATLAB) together with the front end (in the form of MATLAB GUI) is intended to help overcome these limitations. We also restricted the interplay of parameters by scaffolded framework to avoid tricky situations. The users are allowed to tweak only extrinsic parameters such as mass, velocity and initial position of rigid bodies and not intrinsic parameters such as muscle length, tendon length etc. However they can study the effect of these extrinsic parameters on muscle force and muscle power.

B. Scaffolded Graphical User Interfaces

Models will be instantiated from the library during user-interactions with an interface facilitating individualization of interactions to each user. Analyses range from simple collision detection, muscle routings to increasingly complex physical (motion and force) or physiological (muscle activity, tendon-length) investigations. The Graphical User Interface (GUI) now allows for visualization and provides a restricted means for user interaction with AnyBody settings (e.g. using radio controls).

Parametric designs simplify the process of systematic generation of choices especially in a computer-based implementation. However, the appropriate selection of design variables which are both biomechanically relevant and are of significant to the user poses challenges. Design



Fig. 3: The Graphical-User-Interface for supporting the parametric-studies with the Virtual Musculoskeletal Models Framework.

variables can encompass geometry, dynamics as well as regimen parameters. Geometric parameters could include individual user geometries such as limb length, joint angle etc [9, 21], dynamics parameters may include joint velocities, frequency of motion etc [6, 8] while the regimen parameters such as dynamically adjustable springiness, damping and amplitude of a desired motion can also serve as design variables. These design variables can be used to systematically explore the space of feasible alternatives. However, for simplicity, we classify the multiple sets of properties under user control into three broad categories- (A) geometric parameters that include the lengths of various bones, muscles insertion/origin locations etc., (B) dynamics parameters include masses, inertias of the limb as well as stiffnesses and damping properties of the various individual muscles and joints, and (C) regimen parameters include individual joint parameters such as joint velocities as well as global parameters such as cadence.

The GUI permits the user/student to visualize the results of the analysis by multiple modalities. The user can select the type and number of results to be plotted within the output-graphs which are then dynamically updated. Additionally, the motions can also be visualized on VRML representations of the musculoskeletal-subsystem within a 3D graphical window. Additionally a variety of logistics features such as file-handling and saving in a variety of digital formats are also provided.

C. Quantitative Performance Measures

Such tools can now allow monitoring the dynamics of internal human variables (such as muscle-forces and muscle activities). Hence, in this paper, we will use this ‘insight’ into the human models to help study the effects of variability. For example, a tutorial case study might aim to target specific muscle groups of humans. A wide variety of musculoskeletal analysis results (ranging from lengths, forces, reactions of muscles, tendons, joints, etc), can be accessed. However, this raw data needs to be further

processed to create performance measures that can be of utility to the user. Hence, in this paper, (i) muscle forces; (ii) muscle power; will serve as our primary performance measures; alternatively, other higher-level abstracted measures may be developed from the physical measurements of kinematic and dynamic quantities available from the model.

Such performance measures allow a user to directly monitor the effects of a regimen on target muscle groups and allow grasping of functional relationship of muscles. Our goal is to then allow a user to perform parametric studies by varying these parameters, perform analyses on the musculoskeletal models and presenting these results within the GUI (See Fig. 3).

V. VIRTUAL MUSCULOSKELETAL CASE STUDIES

To illustrate the functionality of our overall Virtual Musculoskeletal Models framework, we present the results of our implementation of two case studies:

- (A) Performing a bicep-curl study on the Upper-Arm/Shoulder Musculoskeletal Model; and
- (B) Performing bicycling-motion study on the Lower-Extremity/Hip Musculoskeletal Model.

The selected musculoskeletal-subsystems are not only highly relevant from the pedagogical perspective of “Gross Anatomy” but also stand-out as good examples wherein we study the variability in terms of geometry, dynamics, and regimen.

A. Bicep-curl using the Upper-Arm/Shoulder

For the biomechanical analysis of upper-extremity (See Fig. 4), the biceps curl motion was analyzed based on the design variability selected from each of the three classes of parameters. From the set of geometric parameters, we chose to study the role of the initial elbow joint position; from the dynamics perspective we permit a systematic variation of the mass of the dumbbell; and from the regimen perspective we allow the user to vary the elbow-joint velocity.

	Mass of Dumbbell	Velocity	Initial Position	Peak Muscle Force	Peak Muscle Power
1	0 kg	15 deg/s	90 deg	310 N	-4 W
2	2 kg	15 deg/s	90 deg	370 N	-5 W
3	4 kg	15 deg/s	90 deg	425 N	-5.5 W
4	8 kg	15 deg/s	90 deg	550 N	-7 W
5	10 kg	15 deg/s	90 deg	605 N	-8 W

Table 1: Bicep Curl Model.

The Anybody system allows access to a wide variety of output measures from a host of muscles/joints/segments – however we extract only selected critical quantitative measures (muscle force and muscle power) from selected muscles (Brachialis, Brachioradialis, Biceps short, Biceps long, Triceps short, Triceps long, DeltoideusA and

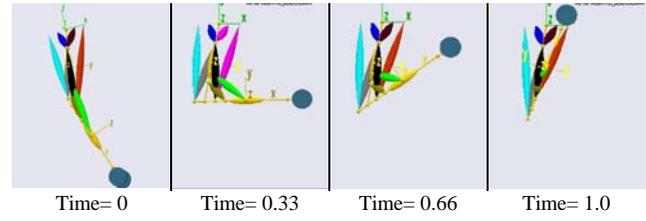


Fig. 4: Visualization of the Biceps Curl as a (normalized) time indexed 3D animation sequences.

DeltoideusB shown in Fig. 6(b)) that play a major role in effecting a curling motion.

Table 1 shows the results of a parametric study of varying the dynamic parameter (dumbbell mass between 0 kg to 10 kg) while keeping the geometric (initial elbow-angle) and regimen (elbow-velocity) parameters at their mid-range values. The resulting graphs of muscle-force and power in the eight principal muscles are plotted for the two analyses (by varying dumbbell masses). The peak values of the muscle-force and power are also tabulated in Table 1 for quick reference. As can be seen, both the muscle forces and powers are lower when the elbow is allowed to curl with lower mass of dumbbell as opposed to when it curls with higher masses.

B. Bicycling motion using the Lower-Extremity/Hip

Similarly, for the lower extremity case we chose the bike model to analyze muscles in both the limbs (See Fig. 5). The model used comprises of Hamstring, Biceps femoris short, Gluteus maximus, Rectus femoris, Vastus lateralis, Gastrocnemius, Soleus and Tibialis anterior muscles shown in Fig. 6(b). In this case we chose study the muscle forces and powers based on the three parameters. We chose to study the role of saddle position (seat height from the crank center), cadence and damping resistance at the crank center.

	Crank Resistance	Cadence	Saddle Height	Peak Muscle Force	Peak Muscle Power
1	2 N-s/ rad	80 rpm	40 cm	3250 N	130 W
2	2 N-s/ rad	80 rpm	50 cm	2200 N	150 W
3	2 N-s/ rad	80 rpm	60 cm	1400 N	170 W
4	2 N-s/ rad	80 rpm	66 cm	1250 N	190 W
5	2 N-s/ rad	80 rpm	70 cm	1100 N	220 W

Table 2: Bike Model.

Table 2 shows the results of a parametric study of varying the geometry parameter (saddle height between 40 cm to 70 cm) while keeping the dynamic (damping resistance at the bicycle crank) and regimen (cadence) parameters at their mid-range values. The resulting graphs of muscle-force and power in the 8 principal muscles are plotted for the two analyses (with saddle height 40 cm to 70 cm). The peak values of the muscle-force and power are also tabulated in Table 2 for quick reference. As can be seen, optimal value of the muscle-force and power are reached when the saddle height is around 66 cm, which actually is the optimum

height for this bike model. From the perspective of training the user/student, this framework can now help reinforce qualitative ideas such as “x% change in parameter results in y% change in result” in a very tangible interactive setting.

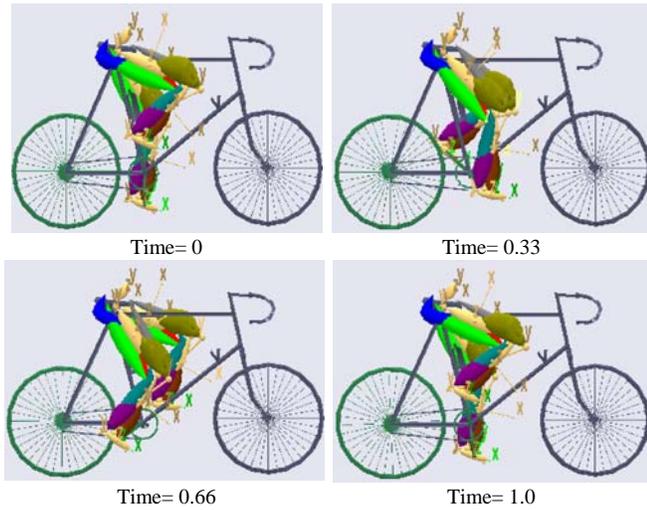


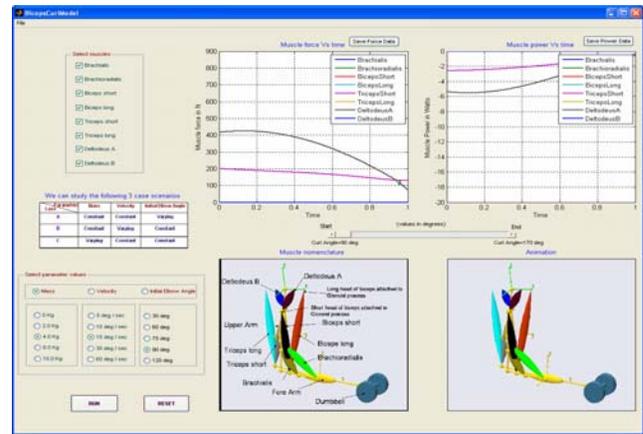
Fig. 5: Visualization of the Bike model as a (normalized) time indexed 3D animation sequence.

VI. CONCLUSION

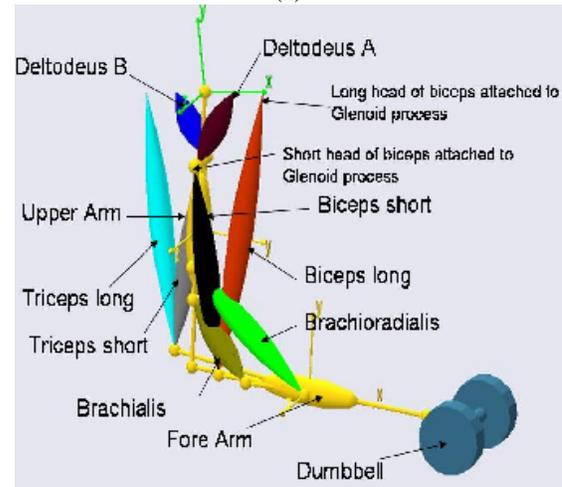
The architecture for scaffolded parametric interaction with detailed virtual-human musculoskeletal models was developed and deployed to make varied “what-if” type analyses and hypotheses testing possible. It was intended to enable the spectrum of the end users (from healthcare students to clinicians) explore the interconnections between form and function in a quantitative computational setting. The immediate goal of our work is to create greater opportunities for enhanced student learning while overcoming issues of limited lab space and times. Ultimately we seek to develop educational technology modules (including the curriculum of laboratory exercises together with a comprehensive implementation guide) will serve as the principal mechanism for dissemination to the research and educational community. At the same time we sought to provide the exposure to realistic experiences with contemporary technological tool.

ACKNOWLEDGMENT

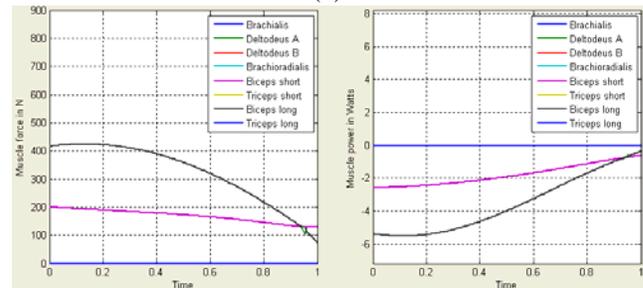
We gratefully acknowledge the use of AnyBody repository models.



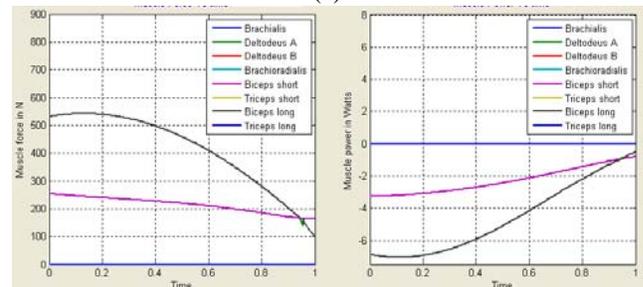
(a)



(b)



(c)

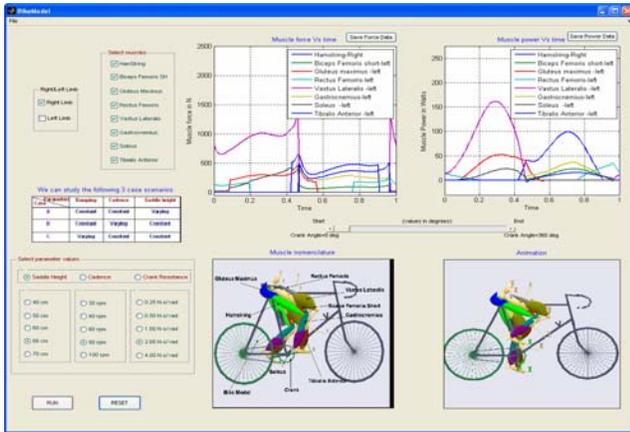


(d)

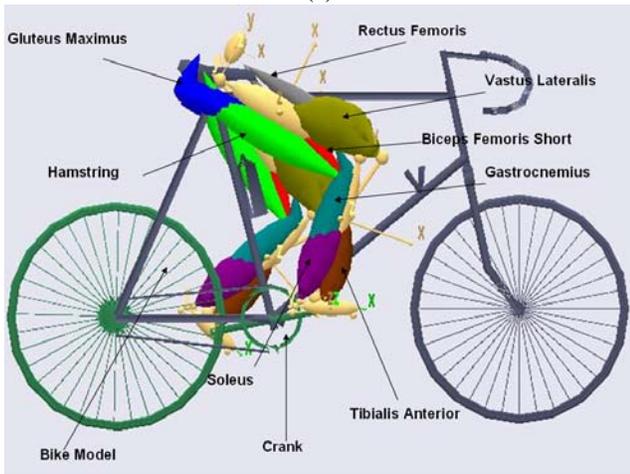
Fig. 6: Case A: Performing a Bicep Curl Study on the Upper-Arm/Shoulder Musculoskeletal Model (a) Graphical User-Interface; (b) Biceps curl model with selected muscles (c) Muscle-force and power for initial elbow angle of 60°; (d) Muscle-force and power for initial elbow angle of 120°.

REFERENCES

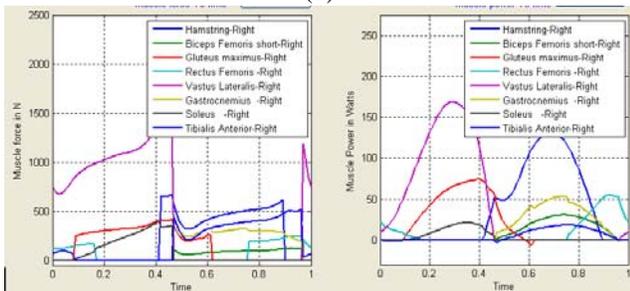
- [1] Musculosgraphics, "SIMM Software Suite," Available: www.musculosgraphics.com, 1992.
- [2] AnyBodyTechnology, "The AnyBody Modeling System," Available: www.anybodytech.com, 2006.
- [3] SimTK, "OpenSim," Available: <https://simtk.org>, 2007.
- [4] S. L. Delp, F. C. Anderson, A. S. Arnold, P. Loan, A. Habib, C. T. John, E. Guendelman, and D. G. Thelen, "OpenSim: Open-source Software to Create and Analyze Dynamic Simulations of Movement," *IEEE Transactions on Biomedical Engineering*, vol. 54, pp. 1940-1950, 2007.
- [5] L.-F. Lee and V. Krovi, "Musculoskeletal Simulation Based Optimization of Rehabilitation Programs," in *Proceedings of the 2006 IEEE International Workshop on Virtual Rehabilitation*, New York City, NY, 2006.
- [6] V. Krovi, G. K. Ananthasuresh, and J. M. Vezién, "Design and Virtual Prototyping of Rehabilitation Aids," *ASME Journal of Mechanical Design* vol. 121, pp. 456-458, 1999.
- [7] R. M. Bhatt, C. P. Tang, L.-F. Lee, and V. Krovi, "A Case for Scaffolded Virtual Prototyping Tutorial Case-Studies in Engineering Education," *International Journal of Engineering Education*, 2006.
- [8] V. Krovi and V. Kumar, "Rapid Design and Prototyping of Customized Rehabilitation Aids," in *Encyclopedia of Microcomputers*, A. Kent, J. G. Williams, and M. Dekker, Eds. New York, NY, 1999.
- [9] V. Krovi, *Design and Virtual Prototyping of User-Customized Assistive Devices* Ph. D. Dissertation Thesis. Philadelphia, PA: University of Pennsylvania, 1998.
- [10] R. Davoodi, I. E. Brown, N. Lan, M. Mileusnic, and G. E. Loeb, "An integrated package of neuromusculoskeletal modeling tools in Simulink," in *23rd Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2001, pp. 1205-1208.
- [11] J. Rasmussen, M. Damsgaard, E. Surma, S. T. Christensen, M. d. Zee, and V. Vondrak, "AnyBody - A Software System for Ergonomic Optimization," in *Fifth World Congress on Structural and Multidisciplinary Optimization*, Lido di Jesolo -Venice, Italy, 2003.
- [12] W. J. Book, K. Koeppen, and M. Rouse, "Virtual Access Hydraulic Experiment for System Dynamics and Controls Education," *Mechatronics*, vol. 12, pp. 261-270, 2002.
- [13] B. J. Furman and G. P. Hayward, "Asynchronous Hands-On Experiments For Mechatronics Education," *Mechatronics*, vol. 12, pp. 251- 260, 2002.
- [14] F. A. Candelas, S. T. Puente, F. Torres, F. G. Ortiz, P. Gil, and J. Pomares, "A Virtual Laboratory for Teaching Robotics," *The International Journal of Engineering Education*, vol. 19, pp. 363-370, 2003.
- [15] L. Whitmann, D. Malzahn, V. Madhavan, G. Weheba, and K. Krishnan, "Virtual Reality Case Study throughout the Curriculum to Address Competency Gaps," *International Journal of Engineering Education*, vol. 20, pp. 690- 702, 2004.
- [16] S. Montgomery and H. S. Fogler, "Selecting Computer-Aided Instructional Software," *Journal of Engineering Education*, vol. 85, pp. 53- 60, 1996.
- [17] A. McKenna and A. M. Agogino, "A Web-Based Module For Teaching Middle School Students Engineering Design with Simple Machines," *Journal of Engineering Education*, vol. 87, pp. 437- 444, 1998.
- [18] R. E. Flori, M. A. Koen, and D. B. Oglesby, "Basic Engineering Software for Teaching ("BEST") Dynamics," *Journal of Engineering Education*, vol. 85, pp. 61-67, 1996.
- [19] J. Rasmussen, J. Dahlquist, M. Damsgaard, M. d. Zee, and S. T. Christensen, "Musculoskeletal Modeling as An Ergonomic Design Method," in *International Ergonomics Association XVth Triennial Conference* Seoul, Korea, 2003.
- [20] J. Rasmussen, J. Dahlquist, M. Damsgaard, M. d. Zee, and S. T. Christensen, "Designing a General Software System For Musculoskeletal Analysis," in *IX International Symposium on Computer Simulation in Biomechanics* Sydney, Australia, 2003.
- [21] N. I. Badler, C. B. Philips, and B. L. Webber, *Simulating Humans: Computer Graphics Animation and Control*: Oxford University Press, USA, 1993.



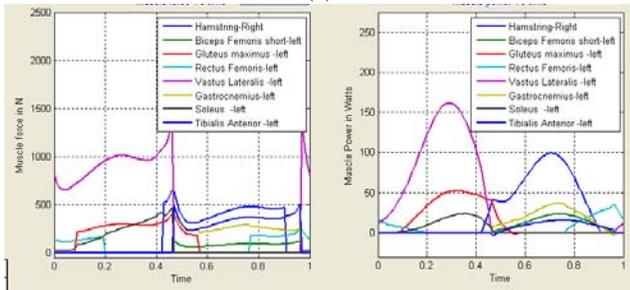
(a)



(b)



(c)



(d)

Fig. 7: Case B: Performing a Bicycling Motion Study on the Lower Extremity/ Hip Musculoskeletal Model (a) Graphical User-Interface; (b) Bike model with selected muscles (c) Muscle-force and power for saddle height of 60 cm; (d) Muscle-force and power for saddle height of 70 cm.