Imagining What 3-D Computer Modelling of Muscle Offers Reconstructive Surgeons

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Digitization in 3D of muscle and skeletal anatomical details can contribute to the creation of anatomically accurate 3D modeling of functioning muscles. Functional muscle modeling with joint movement(s) is in evolution at more than one center including the authors'(1, 2, 4, 5, 23, 24, 30, 32, 35). Clinical data can be integrated into parameterized models from such sources as data mining of image motion capture of individuals (8, 26, 29), multi-dimensionsal imaging studies (ultra sound (9, 21), MRI (5)), and EMG(16) This paper reviews the optimal attributes of muscle function models and emphasizes some clinical, educational, and research uses of realistic modeling of muscle function for reconstructive surgeons.

Desirable attributes for a computer model of a functioning limb include (3, 6, 15, 34):

- The model creates realistic motion given single or multiple muscle excitation(s). This is known as **forward simulation.**
- The model explores and presents the possibilities of muscle excitations that would create a specified motion. This is **inverse simulation.**
- The model explores muscles' function by controlling both neural activation and/or muscle contraction. **Relevant performance ranges** are modelled.
- The model incorporates dynamic function (features that are time dependent) and allows relevant flexibility within interrelated functional control units e.g., the parts of flexor digitorum profundus to the individual digits and the components of partitioned muscles such as the soleus. **Relevant physiology** is included**.**
- The model incorporates in situ volumetric data of the musculotendinous components and their complex relationships. **Relevant anatomy is included.**

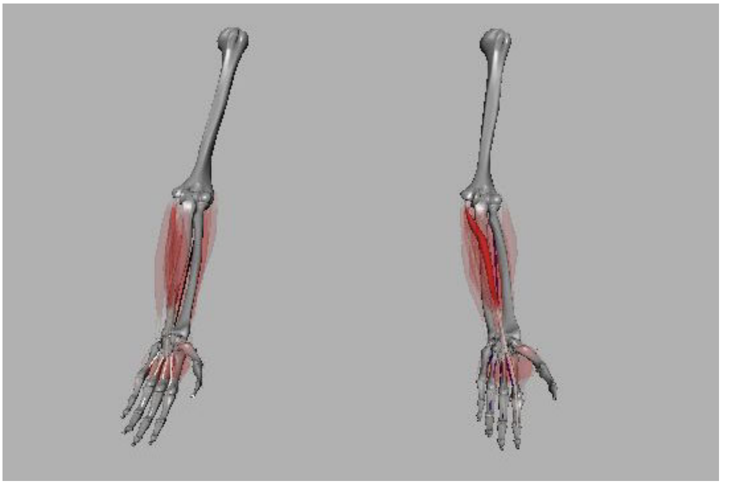

Figure 1 Screen capture of hand model with muscles shaded proportional to activity level. Image cropped so that the computer menus are not shown.

Videos of the authors' model of the 42 muscles of the hand and forearm will be shown to illustrate the potential of 3D computer modeling of functional muscles (figure 1). This computer model has been designed with the capacity of all the above attributes.

The following is a list of some of the possible uses of 3D modeling that a reconstructive surgeon might find helpful.

1) *Assessing functional deficits with existing injury*. Such a computer model can be programmed to mimic any number of tendon and nerve injuries and demonstrate the residual function. This can be compared with the patient's abilities and greater appreciation of the reconstructive needs can be determined.
2) *Planning reconstructive operations* – The design of muscle flaps complete with internal innervation considerations (figure 2) (19) and tendon transfer (7, 17) operations can be explored on a computer model. Sphincter reconstruction including prerequisite forces can be modeled (14). Planning craniofacial reconstruction has been studied from the perspective of the extraocular muscles (27). In free functioning muscle transfers (20) computer modeling could help explore how much of what sort of muscle and where best to attach the origin and the insertion to achieve the desired movement. The precision needed to get the correct result, desirable expression, (11) is very important in muscle balancing operations in the face (13, 31).
3) *Improving functional rehabilitation techniques*. Greater quantification of movement can be acquired by computer assessment of motion analysis and 2 D and 3D ultrasound studies. These studies can demonstrate coordination, range of movement (image motion capture) and the state of contraction and relaxation of muscles (ultrasound)(9). Given this informa-

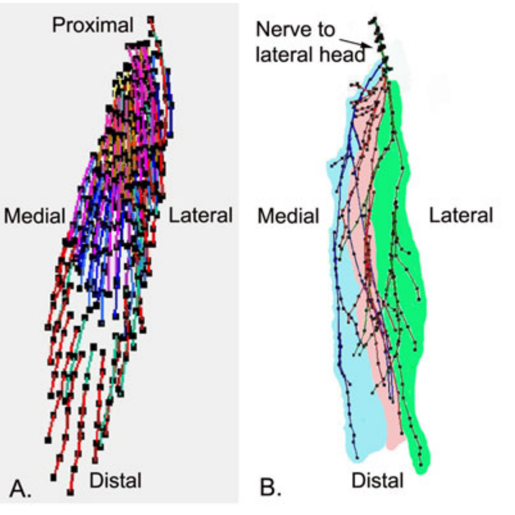

Figure2 3-D modeling of the fiber bundle architecture and innervation of the lateral head of gastrocnemius muscle, posterior views. A. Fiber bundle architecture. Fiber bundles are colored and the digitized points are black. B. Innervation. The nerve distribution (medial, central and lateral) is shown within the volume of the muscle.

tion, a therapist could provide feedback and adjust approaches accordingly. There is the possibility that new training models would be created for athletes after injuries. New insights have been found into focal dystonia (28). The prerequisites for self propelling a wheelchair are being modeled (18).

4) *Educating others about how muscles* do what we so often take for granted. For example : new visuals for teaching medical students and other health care and physical training workers, new understandings of the importance of normal hand gestures (33), exciting new web sites available to all, and new displays at science centers.
5) *Improving understanding* and demonstration *of the word "reconstructive"* that is still key to so much of what we do. This includes the assessment of deficit, consideration of needs, weighing of alternative solutions and designing the optimal use of the chosen approach(es).
6) *Creating data* that permits a framework to assess muscle function in currently minimally treated neuromuscular disorders and be ready to be involved in new possible therapeutic interventions. For example: botox in dystonia and spasticity
7) *Establishing an understanding of muscle function* in humans that will be useful to those who study other species (22, 25).
8) *Influencing the development of animation* of body motion and guitar player (10, 12).

Volume data is also readily available with this modeling approach. Other non-muscle specific models can also be used for assessing dimensions and volume of a reconstruction.

Reconstructive surgeons have often been on the forefront embracing new technologies and capabilities. Computer modeling is another area where creativity and expertise will lead us ahead.

References

1. AGUR AM, et al. Documentation and three-dimensional modelling of human soleus muscle architecture. Clin Anat 16 (4): 285-93, 2003.
2. ALBRECHT I, et al. Construction and animation of anatomically based human hand models. In: Proceedings of SIGGRAPH Symposium for Computer Animation, 2003.
3. ANDERSON FC, PANDY MG. Static and dynamic optimization solutions for gait are practically equivalent. J Biomech 34 (2): 153-61, 2001.
4. BIRYUKOVA E, YOUROVSKAYA V. A model of hand dynamics. Advances in the Biomechanics of Hand and Wrist. New York: Plenum Press, pp. 107-122, 1994.
5. BLEMKER SS, DELP SL. Three-dimensional representation of complex muscle architectures and geometries. Ann Biomed Eng 33 (5): 661-73, 2005.
6. BRAND P, HOLLISTER A. Clinical Mechanics of the Hand. 3rd ed. St. Louis: Mosby - Year Book, Inc., 1999.
7. BRAND PW, et al. Relative tension and potential excursion of muscles in the forearm and hand. J Hand Surg [Am] 6 (3): 209-19, 1981.
8. CARPINELLA I, et al. Experimental protocol for the kinematic analysis of the hand: Definition and repeatability. Gait Posture, 2005.
9. CHOW RS, et al. Sonographic studies of human soleus and gastrocnemius muscle architecture: gender variability. Eur J Appl Physiol 82 (3): 236-44, 2000.
10. COLEMAN P, SINGH K. Technical development for Ryan
11. EKMAN P. Emotions revealed : recognizing faces and feelings to improve communication and emotional life. 1st ed. New York: Times Books, p. xvii, 267 p., 2003.
12. ELKOURA G. Animating the human hand. MSc Thesis, University of Toronto, 2003.
13. GLADILIN E, et al. Anatomy- and physics-based facial animation for craniofacial surgery simulations. Med Biol Eng Comput 42 (2): 167-70, 2004.
14. HELDOORN M, MARANI E. Overview of mathematical computer models of striated sphincter muscles. Arch Physiol Biochem 109 (4): 293-303, 2001.
15. HILL AV. The Effect of Load on the Heat of Shortening of Muscle. Proc R Soc Lond B Biol Sci 159: 297-318, 1964.
16. JOHNSON GR, PANDYAN AD. The activity in the three regions of the trapezius under controlled loading conditions—an experimental and modelling study. Clin Biomech (Bristol, Avon) 20 (2): 155-61, 2005.
17. LIEBER RL, et al. Biomechanical properties of the brachioradialis muscle: Implications for surgical tendon transfer. J Hand Surg [Am] 30 (2): 273-82, 2005.
18. LIN HT, et al. Muscle forces analysis in the shoulder mechanism during wheelchair propulsion. Proc Inst Mech Eng [H] 218 (4): 213-21, 2004.
19. LOH EY, et al. Intramuscular innervation of the human soleus muscle: a 3D model. Clin Anat 16 (5): 378-82, 2003.

20. MANKTELOW RT, et al. Functioning free muscle transplantation. J Hand Surg [Am] 9A (1): 32-9, 1984.
21. MARTIN DC, et al. Comparing human skeletal muscle architectural parameters of cadavers with in vivo ultrasonographic measurements. J Anat 199 (Pt 4): 429-34, 2001.
22. MARZKE MW, MARZKE RF. Evolution of the human hand: approaches to acquiring, analysing and interpreting the anatomical evidence. J Anat 197 (Pt 1): 121-40, 2000.
23. MCKEE NH, et al. Possible uses of computer modeling of the functioning human hand. Clin Plast Surg 32 (4): 635-41, 2005.
24. NEUROMUSCULAR BIOMECHANICS LABORATORY SU. Computational Tools - SIMM (Software for Interactive Musculoskeletal Modeling)
25. NG-THOW-HING V. Anatomically-based Models for Physical and Geometric Reconstruction of Humans and Other Animals. PhD Thesis, University of Toronto, 2001.
26. QIN S, et al. Incorporating 3D body motions into large-sized freeform surface conceptual design. Biomed Sci Instrum 41: 271-6, 2005.
27. SOMANI S, et al. Assessment of extraocular muscles position and anatomy by 3-dimensional ultrasonography: a trial in craniosynostosis patients. J Aapos 7 (1): 54-9, 2003.
28. STINEAR CM, BYBLOW WD. Impaired modulation of intracortical inhibition in focal hand dystonia. Cereb Cortex 14 (5): 555-61, 2004.
29. SU FC, et al. Movement of finger joints induced by synergistic wrist motion. Clin Biomech (Bristol, Avon) 20 (5): 491-7, 2005.
30. THELEN DG, et al. Generating dynamic simulations of movement using computed muscle control. J Biomech 36 (3): 321-8, 2003.
31. TOMAT LR, MANKTELOW RT. Evaluation of a new measurement tool for facial paralysis reconstruction. Plast Reconstr Surg 115 (3): 696-704, 2005.
32. TSANG W. An anatomically accurate inverse dynamics solution for unconstrained hand motion. MSc Thesis, University of Toronto, 2005.
33. WILSON F. The Hand. New York: Panthenon Books, 1998.
34. YAMAGUCHI GT, et al. A computationally efficient method for solving the redundant problem in biomechanics. J Biomech 28 (8): 999-1005, 1995.
35. ZAJAC FE, et al. Biomechanics and muscle coordination of human walking. Part I: introduction to concepts, power transfer, dynamics and simulations. Gait Posture 16 (3): 215-32, 2002.