Learning by doing: construction and manipulation of a skeletal muscle model during lecture

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Rodenbaugh DW, Lujan HL, DiCarlo SE. Learning by doing: construction and manipulation of a skeletal muscle model during lecture. Adv Physiol Educ 36: 302–306, 2012; doi:10.1152/advan.00093.2012.—Active learning, “learning by doing,” enhances student performance on examinations and improves student retention of course content. Active learning also provides inquiry-based, collaborative, and problem-solving activities that promote curiosity, skepticism, objectivity, and the use of scientific reasoning. To incorporate active learning into our undergraduate anatomy and physiology course of 70 nursing students, students constructed working physical models of skeletal muscle during the scheduled class time. Our goals were to actively engage students in the process of building and testing their own mental models from the information they were acquiring. During the process, the focus was on the student acquiring knowledge, thinking about the information, testing assumptions, solving problems, and appreciating the joy, excitement, and love for learning. We conclude that the construction of physical models during class is a valuable educational experience.

THE COMPLEX AND MICROSCOPIC NATURE of the sarcomere is challenging to learn for students who think in terms of what they can see and feel. Students’ overreliance on rote memorization rather than logic, reasoning, deduction, or problem-solving skills results in student difficulties with their ability to translate what they have learned to new situations (24). Educators are encouraged to provide inquiry-based, collaborative, and problem-solving activities that promote curiosity, skepticism, objectivity, and the use of scientific reasoning as a means to promote scientific competencies that emphasize learner performance in areas such as the communication of knowledge, technical skills, or clinical reasoning (1). Transitioning to a competency-based curriculum requires a profound motivation on the part of the teacher to engage students while focusing on concepts that require logic and deduction rather than memorization (6, 24, 31, 44). Replacing memorization in anatomy and physiology classrooms with more problem-solving and constructivist opportunities that emphasize core physiological concepts will result in dynamic classrooms that foster integration of concepts by students (6, 10, 31).

Competency-based curricular change is being advocated at all levels of education. Competency-based curricula value more than just intellectual intelligence—knowing the facts. Competency-based curricula also value factors such as analytic intelligence, emotional intelligence, professionalism, and communication. The incorporation of active learning is a valued component of a competency-based curriculum due to the fact that it addresses many of these outcomes. For example, active learning strategies, including peer instruction (5, 17, 26, 27, 39), collaborative testing (4, 34, 38), construction of physical models (19), and playing educational games (20, 33, 35, 41), have been shown to enhance intellectual intelligence (21, 24, 31). Furthermore, active learning strategies, such as model construction and manipulation, encourage critical thinking, problem solving, collaboration, and interactive learning (19, 32, 36). This is due to the fact that students are actively involved in the development and dynamic application of concepts to the physical model. The construction of physical models provides opportunities for the student to think about the information, engage in the process, develop a functional understanding of the material, use reasoning skills, and practice these opportunities repeatedly throughout the process (2, 3, 7, 12, 14–17, 40, 42). An additional benefit of hands-on active learning is that student motivation is enhanced due to the value-added perception of hands-on learning by students (22). Ultimately, constructing physical models is analogous to preparing a dish as opposed to reading a recipe. Clearly, simply reading a recipe does not provide the same learning experience as preparing the meal (8). Thus, Dr. Arthur C. Guyton’s philosophy of education, learning by doing (18), should be embraced by educators.

To incorporate active learning, “learning by doing,” into our undergraduate anatomy and physiology course of 70 nursing students, students constructed a working physical model of skeletal muscle during the scheduled class time. Our goals were to actively engage students in the process of building their own mental models from the information they were acquiring (29) and constantly testing the validity of the model being constructed.

METHODS

The instructors purchased all materials (Table 1) and prepared “skeletal muscle” packets containing all of the parts for each student before the scheduled class. Each packet (Fig. 1D) had components for half of one sarcomere; therefore, during the construction of the sarcomere and simulation of excitation-contraction coupling, students worked in teams of two.

Assembling the Skeletal Muscle Packets

Table 1 shows a list of the materials and sizes of materials used to create one skeletal muscle packet. All myofilament model materials were collected and prepared before class assembly (Fig. 1A). Six sheets of colored 8 × 11-in. paper were rolled into separate tubes, which were fixed with tape. The myofilament materials were packed into these six tubes (Fig. 1B). Each tube was then individually wrapped in thin Saran Wrap to represent a muscle cell. These six tubes...
Muscle cell components used to represent the myofilament components were prepared. Fig. 1. Process for assembling the “skeletal muscle” packets. The model components were wrapped together with one piece of heavy-duty Saran Wrap (Fig. 1C) to represent a fasciculus. Finally, a piece of aluminum foil was wrapped around a fasciculus to create a skeletal muscle packet, which was given to the student (Fig. 1D).

**Class Activity**

During class, the instructor used the “Socratic” method, teaching by asking rather than by telling, to discuss the anatomy and physiology of skeletal muscle. As part of the discussion, students were instructed to unwrap their skeletal muscle packets and construct the physical model of a sarcomere.

**Connective tissue.** Starting from the outside of the skeletal muscle packet and moving inward, the students first unwrapped the “epimysium” (aluminum foil), which, in the body, is composed of dense, collagenous connective tissue and covers the entire surface of the muscle (Fig. 1D). Removing the epimysium exposed the “fasciculus.” A fasciculus is a small group of muscle fibers that are made up of groups of muscle cells. Each fasciculus in the skeletal muscle packet is a bundle of six “muscle cells” encased together in dense heavy-duty Saran Wrap. The dense heavy-duty Saran Wrap represents the “perimysium.” The perimysium was unwrapped, exposing the cylindrical muscle cells. Each muscle cell was wrapped in thin Saran Wrap, representing the endomysium (Fig. 1C). Students removed the endomysium from the individual muscle cells to gain access to the myofilament components packed into these muscle cells (Fig. 1B).

**Assembling the skeletal muscle myofilament components.** The muscle cells (paper cylinders) were stuffed with the components shown in Fig. 1A. These included two Z lines and one M line (three long green twist ties of ~15 cm long), “troponin” (four strands of three small black beads), “tropomyosin” (two ~6-cm-long blue twist ties), “actin” (the thin myofilament; 4 strands of 21 red beads/strand), “myosin” (the thick filament; 6 pipe cleaners), and four ~2-cm-long blue twist ties, which were used to secure actin to troponin.

During class, each component shown in Fig. 2 was discussed in detail. While these components were discussed, individual students were asked to identify these components in their model and begin to assemble the components based on the descriptions given in class (Fig. 2). For example, each F-actin strand is a polymer of small globular units called globular actin (G-actin, the beads on the strand

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**Table 1. Supply list for the skeletal muscle packet**

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myofilament proteins</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Z-line and M-line</td>
<td>3</td>
<td>15 cm</td>
<td>Green twist tie</td>
</tr>
<tr>
<td>Actin</td>
<td>4</td>
<td>Strand of 21 beads</td>
<td>Medium red beads</td>
</tr>
<tr>
<td>Myosin</td>
<td>6</td>
<td>Large</td>
<td>Heavy duty pipe cleaner</td>
</tr>
<tr>
<td>Tropomyosin</td>
<td>2</td>
<td>6 cm</td>
<td>Blue twist tie</td>
</tr>
<tr>
<td>Troponin</td>
<td>4</td>
<td>Strand of 3 beads</td>
<td>Small black beads</td>
</tr>
<tr>
<td>Muscle cell</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paper rolls</td>
<td>6</td>
<td>8 x 11 in.</td>
<td>Colored paper rolls</td>
</tr>
<tr>
<td>Thin Saran Wrap</td>
<td>6</td>
<td></td>
<td>1 piece wrapped around each paper roll</td>
</tr>
<tr>
<td>Muscle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Heavy-duty Saran Wrap</td>
<td>1</td>
<td></td>
<td>1 piece wrapped around 6 muscle cells to form the fasciculus</td>
</tr>
<tr>
<td>Aluminum foil</td>
<td>1</td>
<td></td>
<td>1 piece wrapped around the fasciculus</td>
</tr>
</tbody>
</table>

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**Fig. 1.** Process for assembling the “skeletal muscle” packets. The model components used to represent the myofilament components were prepared. A (from top to bottom): long green twist ties (Z lines and M line), medium blue twist ties (tropomyosin), small blue twist ties (protein used for binding, as shown in Fig. 2), black beads (troponin), red beads (actin), and white pipe cleaners (myosin). B: individual muscle cells were represented by forming paper tubes, which were packed with the myofilament protein components. Each cell was wrapped in thin Saran Wrap. The thin Saran Wrap represents the endomysium. C: a group of six endomysium-wrapped muscle cells was collected and wrapped in a piece of heavy-duty Saran Wrap to represent a fasciculus, which contains bundles of muscle cells encased in the perimysium. D: a piece of aluminum foil was then wrapped around the fasciculus to represent the epimysium, which covers the entire surface of a muscle.

**Fig. 2.** Assembled individual myofilament components used to create a sarcomere. Two strands of red beads were twisted together several times to represent F-actin. The twisting creates grooves into which the strands of black beads are placed to represent the troponin complexes. The medium-sized (6 cm) blue twist ties that represent the tropomyosin molecules span the length of the F-actin within the groove as well. The remaining four short (2 cm) blue twist ties are used to bind the model together (F-actin + tropomyosin + troponin). Myosin filaments (pipe cleaners) were composed of two pipe cleaners shaped like golf clubs. Each myosin consisted of two “heavy myosin molecules,” pipe cleaners wound together to form a “rod portion” lying parallel to the myosin myofilament and two “heads” (ends of pipe cleaner shaped like the ends of a golf club) that extended laterally.
of red beads). Each G-actin monomer has an active site to which myosin molecules can bind during muscle contraction.

Troponyosin (~6-cm-long blue twist ties) is an elongated protein that winds along the groove of the F-actin double helix (2 strands of 21 red beads/strand wound together). Each troponyosin molecule was long enough to cover seven G-actin sites (7 beads on a strand). Troponin (strands of 3 small black beads) was composed of three subunits: one subunit that binds to actin, a second subunit that binds to troponyosin, and a third subunit that binds to calcium. As shown in Fig. 2, all binding was accomplished with the use of short twist ties. The troponin molecules (strand of 3 small black beads) were spaced between the ends of the troponyosin molecules (~6-cm-long blue twist ties) in the groove between the F-actin strands (2 strands of 21 red beads).

Each myosin molecule consisted of two “heavy myosin molecules,” pipe cleaners wound together to form a “rod portion” lying parallel to the myosin myofilament and two “heads” (ends of pipe cleaner shaped like the ends of a golf club) that extended laterally (Fig. 2). Myosin filaments (pipe cleaners) were composed of six pipe cleaners shaped like golf clubs (Fig. 3).

Assembly of the skeletal muscle sarcomere model. During class, the sarcomere was discussed in detail. While the components of the sarcomere were discussed, students were asked to assemble their myofilament components into a model that represents one half of a sarcomere. For example, a sarcomere extends from one Z disk to an adjacent Z disk (Fig. 3). A Z disk is a filamentous network of proteins forming a disk-like structure for the attachment of actin myofilament (wound double strands of 21 red beads). The Z disk is used to anchor the two actin filaments in place (Fig. 3). The arrangement of actin myofilaments and myosin myofilaments gives the myofibril a banded, or striated, appearance when viewed longitudinally. Each isotropic (light) band, or I band, includes a Z Disk and extends from either side of the Z disk to the ends of the myosin myofilament. Each anisotropic (dark) band, or A band, extends for the length of the myosin myofilament. As shown in Fig. 3, the actin and myosin myofilaments overlap at both ends of the A band. In the center of the A band is a smaller band, labeled the H zone, where actin and myosin myofilaments do not overlap and only myosin myofilaments are present. The band in the middle of the H zone is labeled the M line. The M line (long green twist tie) consists of filaments that attach to the center of the myosin filaments. The M line holds the myosin myofilaments in place, similar to the way that the Z disk holds the actin myofilaments in place.

![Fig. 3. Pairs of students collaborated to create a model representing a sarcomere using their individual model components from their skeletal muscle packet. A sarcomere extends between two Z disks. Both students should connect their actin + troponin + troponyosin complexes to the twist ties, which are bent to represent the Z disks. Students use the remaining green twist tie to combine both myosin complexes at the M line in a manner that creates the H zone. Students should arrange both complexes in a manner where some of the pipe cleaner “myosin heads” are able to interact with the F-actin complexes. However, some room must be left between the Z disk and the ends of the myosin complexes to create the I band. The A band is the region of the sarcomere where there is no overlap between actin and myosin.](image)

Collaborative assembly of a sarcomere to review the sliding filament model. At this point, each student has constructed half of one sarcomere. Students now formed collaborative groups of two to complete the sarcomere (Fig. 3) and simulate the sliding filament theory.

The sliding filament model of muscle contraction includes all of the events that result in actin myofilaments sliding over myosin myofilaments to shorten the sarcomeres of muscle fibers. By manipulating their model, students observed that actin and myosin myofilaments do not change length during contraction. Students observed that actin and myosin slide past one another in a way that causes the sarcomere to shorten (Z disks move toward one another). As the students slid the actin myofilament over the myosin myofilament, they noted that the myofilaments do not change length and that the actin myofilaments at each end of the sarcomere slide past the myosin myofilament toward each other. As a result, the two Z disks are brought closer together, and the sarcomere shortens. As the actin myofilaments slide over the myosin myofilaments, the H zone and I bands narrow. The A bands, which are equal to the length of the myosin myofilaments, do not narrow, because the length of the myosin myofilaments does not change. Finally, in the fully contracted state, students observed that the ends of the actin myofilaments overlapped and the H zone disappeared.

Excitation-contraction coupling. Action potentials produced in the sarcolemma of a skeletal muscle fiber can lead to contraction of the fiber. The mechanism by which an action potential causes contraction of muscle fibers is called excitation-contraction coupling, and it involves the T tubule, sarcoplasmic reticulum, Ca^{2+}, and troponin (none of which are included in this model). The use of animations or additional models may be used to expand the conceptual framework of the model in class.

RESULTS AND DISCUSSION

Seventy undergraduate nursing students and the teacher, using an active learning strategy, constructed working physical models of the skeletal muscle during the scheduled class time. Specifically, the students, working together and guided by the teacher, identified the anatomy by gathering information, learning from it, and applying new information in a novel way. The teacher facilitated the process by asking questions that guided the students toward the development of their own conclusions. This active learning strategy is of particular value for complex and microscopic anatomy, such as the sarcomere, when the structures are impossible to dissect or when two-dimensional pictures cannot replicate the anatomy in three dimensions or communicate how components relate spatially.

Physical models encourage research oriented learning and are often used to explain complex ideas because models promote logic, reasoning, and creativity (2, 3, 9, 12–14, 16, 37, 40, 42, 43) by relating the unknown to the familiar and providing a new perspective on information gathering. Active participation with physical models can engage and reach all types of learners via the visual, auditory, kinesthetic, and tactile schemes of learning (25). Specifically, the instructor noted a high degree of student engagement during the process of construction and manipulation of the sarcomere model relative to past didactic lecture experiences regarding the same subject material. Classroom engagement was apparent based on the level of student attentiveness to the instructor, the quantity and quality of peer-peer communication, and the discussions that arose as students not only used the model materials to create physical representations of what they conceptualized but also as the student teams compared and contrasted their levels of understanding while working on the model. The multiple-input
experience encouraged exploration, discovery, and inquiry into complex processes while accommodating a wide range of learning styles (23). Finally, three-dimensional physical models can be more helpful than two-dimensional images in the learning and retention of anatomy content (11).

It is important to note that the entire process required more time than what would have been required for the same content during a traditional lecture (28). Specifically, the quantity of material presented could easily be completed within 50 min by simply presenting the facts. This would involve transferring the information from the teacher’s notes to the notes of the student without having the information ever go through the minds of either the teacher or the students, that is, without students having spent time thinking about the information. In this setting, presenting the facts is different from students understanding the concepts. For students to understand the material, they must have time to process the ideas.

Time constraints place a limit on the breadth of material that can be covered. The limitation on the breadth of material covered is a major concern for many faculty members, who believe that if “we” (the teachers) don’t say “it” in class, the students won’t learn “it” (30). Furthermore, if the primary goal of our course is to ensure that the students “get” all of “it,” we must mention all of “it” in class, lest we fail in reaching our objectives (30). This approach, “the mile wide but inch deep philosophy,” limits deep conceptual learning. In contrast, the mile deep and inch wide approach encourages meaningful learning, or learning with understanding (29), and creates a desire to know.

Furthermore, it is clear that active processing of information and not just passive reception of that information leads to learning. That is, we understand and remember the information we think about because understanding is the residue of thinking (8)! Specifically, learning with understanding requires time. Teachers must be realistic about the amount of time required to learn complex concepts and provide the time to achieve the goal (8). Students need time to explore underlying concepts and to generate connections to other information. Students must have time to “grapple” with specific information relevant to the topic. Thus, learning cannot be rushed; the complex cognitive activity of information integration requires time (8).

To encourage the use of active learning strategies by more instructors, we must address this time concern. To address this concern, we should note that only a small portion of the current body of medical knowledge can be taught in 4 yr and that not all that is taught is learned or remembered (45). Some of what is taught is erroneous, and other material will soon be obsolete. Furthermore, much of the knowledge that will be used in students’ future careers is not known today and therefore must be learned after graduation (45). Thus, the notion that all relevant content must be presented in class is flawed, especially since the relevant content for a given class changes from year to year. These facts are why we need to recognize the importance of helping students become lifelong learners. Active learning takes responsibility for learning away from the instructor and gives it to the student. The incorporation of active learning strategies in a class helps students develop the skills they will apply to voluntary self-motivated learning that will be required outside of classroom. Students must take responsibility for their learning and engage in the process of self-learning (30). In this setting, students become capable of working together and gathering evidence, evaluating it and learning from it, that is, developing the metacognitive skills that will help them become lifelong learners.

**Limitations and Suggested Model Concept Modifications**

Educational models can be limited with respect to capturing all aspects of a process. This is especially true when low-fidelity models attempt to capture features of structure and function at the microscopic level (21). For example, the model described in this article emphasizes the compartmentalization and biomechanical aspects of excitation-contraction coupling at the level of the sarcomere. However, the model does not address other aspects of excitation-contraction coupling (e.g., structures such as the t-tubules or sarcoplasmic reticulum or the role of ions, such as Na⁺ or Ca²⁺, in muscle contraction). In addition, the model does not represent the three-dimensional arrangement of actin and myosin (21). Thus, instructors choosing to use this model are encouraged to be creative and consider modifications that suit their curricular needs. Alternatively, instructors may couple this hands-on model with animations and/or computer simulations that would address concepts not represented by the model. Another idea may be to create a class project that asks teams of students to be creative and modify the model in a manner that includes an aspect of excitation-contraction coupling not represented by this model, such as the sarcoplasmic reticulum. At a minimum, instructors need to be prepared to discuss the limitations of models used in class that integrate structure and function. Finally, this muscle model provides a prototype of a technique that could be used to learn anatomy and physiology through building of an organ or tissue and examining its properties.

**DISCLOSURES**

No conflicts of interest, financial or otherwise, are declared by the author(s).

**AUTHOR CONTRIBUTIONS**

Author contributions: D.W.R., H.L.L., and S.E.D. analyzed data; D.W.R., H.L.L., and S.E.D. interpreted results of experiments; D.W.R., H.L.L., and S.E.D. prepared figures; D.W.R., H.L.L., and S.E.D. drafted manuscript; D.W.R., H.L.L., and S.E.D. edited and revised manuscript; D.W.R., H.L.L., and S.E.D. approved final version of manuscript; H.L.L. and S.E.D. conception and design of research; H.L.L. and S.E.D. performed experiments.

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How We Teach

ACTIVE LEARNING OF MUSCLE STRUCTURE AND FUNCTION