An inexpensive 2-D and 3-D model of the sarcomere as a teaching aid

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Rios VP, Bonfim VM. An inexpensive 2-D and 3-D model of the sarcomere as a teaching aid. Adv Physiol Educ 37: 343–346, 2013; doi:10.1152/advan.00111.2012.—To address a common problem of teaching the sliding filament theory (that is, students have difficulty in visualizing how the component proteins of the sarcomere differ, how they organize themselves into a single working unit, and how they function in relation to each other), we have devised a simple model, with inexpensive materials, to be built by students in the fourth year of an undergraduate biology course. This model can be quickly built by the students themselves and is functional enough to allow visualization of the filaments and their properties. The model uses cheap, simple materials, mostly party and craft supplies, to simulate the component proteins of the sarcomere, and the proposed materials can be readily replaced by more available ones.

sarcosome; actin; myosin; teaching tools; muscle contraction; two-dimensional; three-dimensional

THE MUSCULOSKELETAL SYSTEM is responsible for the body’s movements and locomotion in vertebrates. Even though there are different types of muscles, with differing cellular structures (skeletal striated, cardiac striated, and smooth muscles), all muscles share the same basic traits regarding their contractile properties. All muscles possess actin and myosin, even though different classes of these proteins may be expressed in different cells, and these proteins are arranged in such a way that allows the proteic filaments to slide over one another, thus shortening the cell. In striated muscle cells, this arrangement is more pronounced, and more easily visualized, forming the structure known as the sarcomere. The aligned sarcomeres shorten, with the myosin filaments sliding over the actin ones, thus shortening the whole cell, in a process known as muscle contraction.

To understand how contraction happens, it is important to understand the structure and mechanics of the proteins involved. In addition to myosin and actin, a series of other proteins is also present, helping to organize and stabilize the sarcomere. Actin is present in the form of long thin filaments, over which are laid filaments of tropomyosin and groups of troponin. During the relaxation period, troponin covers the active site of myosin, keeping the myosin heads from bonding with it; in the presence of Ca2+, tropomyosin dislocates the troponin complex, permitting contraction. Thin filaments are also associated with other different proteins, namely, tropomodulin and CapZ, which prevent it from depolymerizing, and nebulin, which serves as a kind of ruler when the sarcomere is being formed, determining the length of the actin filaments.

Several actin filaments are linked to a region called the Z-disk, which serves as a separator between independent sarcomeres, helping it to maintain its structural integrity. Myosins are linked together to form the thick filament, with myosin heads facing opposite sides. These heads move in the presence of ATP, successively bonding with and releasing actin’s active site when they are not covered by troponin. It is this movement of bonding and releasing that causes the sarcomere to shorten, resulting in contraction. The thick filament is connected to the Z-disk via titin, a long, elastic protein that helps to maintain the sarcomere’s stability (7, 10, 14).

However, these proteins are microscopic structures and cannot be studied in detail even with the most potent optical microscopes; therefore, these mechanisms are taught to students using drawings, schematics, or computer animations. Moreover, animal physiology teachers have to face the problem of not being allowed to use live animals or animal preparations during experiments, due to negative student reactions or institutional regulations. Thus, many teachers have turned to using “virtual animal” models or videos of previous experiments. These, however, are mostly passive teaching tools and may sometimes fail to properly engage students in the activity. Here, we describe a fairly simple and reasonably accurate model that can be used to teach sarcomere structure and sliding filament theory and can be built by the students themselves. The materials used can also be readily adapted to teach other proteic structures, such as the cytoskeleton.

The use of a two-dimensional (2-D) or three-dimensional (3-D) tangible, movable model is a great addition to a class and helps students to cement concepts more easily, and engaging more sensory modalities helps students to assimilate contents better (3, 11).

MATERIALS AND METHODS

During the years of 2011 and 2012, we gave students in the Comparative Animal Physiology class of the Biological Sciences course at the Federal University of Bahia (divided in 3 classes/semester) illustrations from three animal physiology textbooks (7, 10, 14) depicting the structures of each protein and of the whole sarcomere to guide them throughout the building of the model. We then gave students the materials shown in Fig. 1 to assemble as they pleased. Students chose how to build the model and which parts to use based on the illustrations given, and, after building the filaments, they were asked to explain the functioning of the parts they chose to represent and what role they played in the contraction process. They were free to choose whether to build a 2-D or 3-D model, with the caveat that the model would have to be functional, i.e., the filaments would have to be able to slide over each other to depict the contraction process. We describe below one way of building the model, but the parts used and their assembly can be easily changed for other materials, as available.

Thin filaments. The thin filaments (Fig. 2A) are made of two hot glue sticks each, twisted together to represent the turns of the actin filament. The sticks are held together at the ends by pins with colored heads, which represent tropomodulin and CapZ proteins, preferably with a different color for each protein. Wooden sticks of the same...
length as the twisted hot glue sticks are used to represent nebulin. The tropomyosin filament is represented by a colored thread that runs through the length of the twisted glue stick, accompanying the turns. Colored beads are used to represent the troponin complex, and they can be glued on equal spaces along the tropomyosin filaments, or one can pass the colored thread through the beads, forming a sort of collar to represent the relation between troponin and tropomyosin. Different-sized beads can be used to represent the different troponin subunits, but this is usually not necessary. The assembled thin filament models are then glued together with nebulin using hot glue on a supporting plate, which can be made of wood, styrofoam board, or any other material able to support the weight, like plastic dishes. This supporting plate represents the Z-disk. Usually two thin filaments per side of the sarcomere are sufficient to create a working 2-D model of the sarcomere, but we recommend building a 3-D model, which would require a total of at least 12 such filaments plus a central thick filament.

**Thick filaments.** The thick filament (Fig. 2B) is built using bendy plastic straws and tiny plastic spoons. The bendy straws have a mobile neck, which adequately represents the myosin neck, and small plastic spoons are inserted into these necks to represent the myosin heads. This allows us to use the model to demonstrate the full contraction cycle, with the conformational changes that proteins suffer throughout these cycles. A bundle of these myosin models is then glued together with the heads oriented correctly, and two of these bundles are glued end to end, to represent the full thick filament. Titin is represented by tubular balloons, of the kind used to make balloon animals. These balloons are glued to the Z-disk plate and the thick filament. In the 2-D model, one balloon should suffice per side, but for a 3-D model, it is best to braid a few balloons together for added strength and resistance, since it is these balloons that will have to support the weight of the thick filament.

With the filaments ready, it is merely a matter of putting them together to assemble the sarcomere (Figs. 3 and 4).

**RESULTS**

Students showed great enthusiasm in building the model and, when asked about it, reported that the model-building activity helped them to better understand the basics of muscle contraction. Also, since students were free to use the materials as they pleased, there was variation in the models built (Figs. 2 and 3), and students showed the desire to take their models home with them. One group, for instance, chose to represent the actin-binding sites of the myosin head using a bit of modeling clay, and another group decided to use the modeling clay.
clay to represent troponin instead of the colored beads originally supplied for that.

During one of the classes, we presented an open questionnaire to the students to assess student engagement and evaluation of the activity (see Table 1). All of the students (100%) evaluated the model-building activity positively overall, stating that the activity helped them to better comprehend and visualize the functioning of the sarcomere. All of the students (100%) responded positively to the question “In your opinion as a student, does building and using physical models help generating interest on the subject and aid in comprehension of the subject matter?” Negative comments were few (14%) and mostly related to the fact that the activity was done immediately after the first lecture on the subject.

DISCUSSION

Presently, the use of ludicity in education has been gaining attention in different segments of education studies, such as the teaching of science, and it is also a necessity for social context. The essence of ludicity lies in the interactive processes performed by the individual. In other words, learning happens through students’ direct and indirect interactions with the object under study (4). Asbel’s cognitive-constructivist theories emphasize the importance of students’ previous knowledge for the anchoring process of new information, which is the fundament of meaningful learning, i.e., new information is linked with a relevant aspect of the individual’s knowledge structure (1). In the meaningful learning theory, problem solving helps to organize information, in that this task stimulates the subject’s cognitive structure and incorporates the new information into it (8).

The use of problem solving and ludicity as a tool for meaningful learning facilitates the constructive processing of information, since solving problems, either teacher given or created by the student, as part of learning strategies helps to motivate and engage students, allowing them to approach different subjects through different viewpoints and to learn and convert concepts, propositions, and examples into actions via interactions with teachers, classmates, and teaching materials (12, 13). The teacher’s role shifts from that of being the main vehicle of information to that of a mediator of access to information and an instructor of classroom activities, putting the student at the forefront of the construction of his/her own knowledge. The subject’s active role and the central role given to discovery and exploration are seen as decisive in the learning process (2, 13). This way, it is important that teachers do not interfere with the model-building process, even if it is obvious to them that the final model will not be able to function as intended (5). In our case, the intended functionality is that the students be able to demonstrate the contraction process and the function of the proteins involved. In fact, a “failed” model, i.e., a model missing essential proteins or with proteins arranged in a way which does not allow for contraction, can be a powerful teaching tool, as the students will have to figure out what went wrong that caused the model to not function properly, further helping the learning process and enhancing the students’ understanding of the role that each protein plays in the sarcomere.

Involving the students in the creative model-building process increases student interest in the subject matter and brings the abstract concepts of textbooks closer to the students’ reality (9), by making tangible a part of physiology that cannot easily be seen in living tissue, be it with the naked eye or using optical microscopy. In our experience, due to the nature of the curriculum of the undergraduate biology course on which we tested these models, which places comparative animal physiology at the end of the course, when students have already decided their future areas of work, students have a low interest in actually learning animal physiology instead studying only enough to have a passing grade. It is not unusual to hear these students say “I’m not going to use any of that in my life, because I study botany/systematics/human genetics/etc., so why should I study that?” The model-building activities engage these students by turning a subject that could otherwise be boring and memorization based into a hands-on activity, which gives them a tangible result, and since they have to link the form of their models to the function of its parts, they learn the contents better. The teacher should stimulate students to realize and explain inconsistencies between the physical model and those presented in textbooks, such as matters of scale and proportions between the proteins represented, which are distorted due to the materials used, or the fact that the actin filament is not a cylinder, as represented by the glue sticks, but closer in shape to a twisted bead necklace. Despite these incongruences, the parts

Table 1. Evaluation questionnaire

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<tr>
<th>Question</th>
<th>Percentage of Positive Answers</th>
<th>Significant Remarks</th>
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<tr>
<td>1. Did you have any difficulty in building and/or understanding the model? Which ones?</td>
<td>57.2</td>
<td>Most positive responses had to do with not being used to using creativity and to the fact that the model was built right after the subject was first introduced</td>
</tr>
<tr>
<td>2. Has building the model helped you to understand the structure of the sarcomere and of the associated proteins?</td>
<td>100</td>
<td>Most of the students said that the activity helped them to better visualize and understand the sarcomere’s structure</td>
</tr>
<tr>
<td>3. Did the model’s functioning help you understand the functioning of the sarcomere and of the associated proteins?</td>
<td>100</td>
<td>Most of the students said that the activity helped them to better visualize and understand the sarcomere’s functioning</td>
</tr>
<tr>
<td>4. In your opinion as a student, does building and using physical models help to generate interest on the subject and aid in comprehension of the subject matter?</td>
<td>100</td>
<td>Some students stated that model building helped them to visualize the microscopic structures, and some students stated that the ludic aspect of the activity helped to generate interest</td>
</tr>
<tr>
<td>5. Evaluate the practice freely, highlighting the positive and negative points, and say what you would suggest to improve it.</td>
<td>100</td>
<td>The negative point most cited was the fact that the activity was performed right after the subject was first introduced</td>
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The sample size was seven students from one class, which were presented a lecture on the sarcomere right before the activity. Questions were open ended; thus, not all students gave much detail on their thoughts about the model-building exercise. Students did not have identify themselves on the answer sheet.
of the model serve their purpose well, representing the mechanics of the proteins after which they were modeled. The movable myosin heads provided by the bendy straws as well as the moveable strings and beads that represent the troponin-tropomyosin complex can be manipulated to show how the cross-bridges work, how the filaments slide over each other, and the subsequent shortening of the sarcomeres.

The model presented here is easy to make and can be adapted to use different materials while maintaining a reasonably accurate representation of the structure and mechanics of the proteins involved in the contraction cycle. According to Rice (12), “playful learning can enrich and augment existing approaches to learning for students in higher education.”

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DISCLOSURES

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

AUTHOR CONTRIBUTIONS

Author contributions: V.P.R. and V.M.G.B. conception and design of research; V.P.R. and V.M.G.B. performed experiments; V.P.R. and V.M.G.B. analyzed data; V.P.R. and V.M.G.B. interpreted results of experiments; V.P.R. and V.M.G.B. prepared figures; V.P.R. and V.M.G.B. drafted manuscript; V.P.R. and V.M.G.B. edited and revised manuscript; V.P.R. and V.M.G.B. approved final version of manuscript.

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