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Combining High-Speed Cameras and Stop-Motion Animation Software to Support Students' Modeling of Human Body Movement

Victor R. Lee

Abstract Biomechanics, and specifically the biomechanics associated with human movement, is a potentially rich backdrop against which educators can design innovative science teaching and learning activities. Moreover, the use of technologies associated with biomechanics research, such as high-speed cameras that can produce high-quality slow-motion video, can be deployed in such a way to support students' participation in practices of scientific modeling. As participants in classroom design experiment, fifteen fifth-grade students worked with high-speed cameras and stop-motion animation software (SAM Animation) over several days to produce dynamic models of motion and body movement. The designed series of learning activities involved iterative cycles of animation creation and critique and use of various depictive materials. Subsequent analysis of flipbooks of human jumping movements created by the students at the beginning and end of the unit revealed a significant improvement in both the epistemic fidelity of students' representations. Excerpts from classroom observations highlight the role that the teacher plays in supporting students' thoughtful reflection of and attention to slow-motion video. In total, this design and research intervention demonstrates that the combination of technologies, activities, and teacher support can lead to improvements in some of the foundations associated with students' modeling.

Keywords Biomechanics · High-speed cameras · Slow-motion video · Modeling · Animation · Elementary schools

V. R. Lee (✉)
Utah State University, Logan, UT, USA
e-mail: victor.lee@usu.edu

Introduction

Over the past several years, there has been a growing recognition among education researchers that bodily activity can serve as an important, and often underutilized, resource for teaching and learning (e.g., Richland et al. 2007). The observation that bodily experience can be critical to learning is one that has actually been made many times before, with attribution even going as far back as Piaget (1929) who asserted sensorimotor learning as an important part of cognitive development. Yet, there is also much contemporary interest. Over the past decade, the confluence of increased scholarly attention to the field of embodied cognition (e.g., Barsalou 1999; Hall and Nemirovsky 2011) and more deliberate efforts to design and integrate new "body-centric" technologies into learning environments has demonstrated some of the new pedagogical possibilities for turning bodily activity into an object of inquiry and reflection (e.g., Abrahamson 2009; Enyedy et al. 2012; Lee and DuMont 2010; Moher et al. 2014).

This article reports on a comparable design effort to introduce a technology-supported, elementary classroom unit that required students to become reflective about their bodily activities and use visual body movement data that they obtained to take initial steps toward scientific modeling of complex body movements. There are several reasons why such an effort is timely and appropriate with relevance to educators. First, if we take seriously that there is indeed real potential for students to bootstrap understandings by means of inspection of records associated with their own bodies (Lee 2013), then we need more concrete strategies for how schools and classrooms could facilitate this in a scalable way. Second, with the release of the Next Generation Science Standards (Achieve 2013), identifying new ways for students to participate in scientific

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practices—such as modeling—within the context of specific science content investigations is now an imperative for science educators. While the path toward competency in scientific modeling can follow many different possible developmental pathways that will depend on the content being addressed, there does seem to be widespread agreement that the production of an external representation from records of observed phenomena is a critical starting place for students who are involved in modeling (e.g., Lehrer and Romberg 1996; Schwarz et al. 2009). That is, an initial step toward proficiency with scientific modeling involves students creating their own depictions that account for a set of observations.

Given that observing phenomena and creating a representation of that phenomenon are essential, it follows that there could be some fundamental and straightforward ways in which technology can play important roles. Namely, technology could be used to collect observational records. It could also be used as an expressive medium for eventual depiction of new representations. For this project, high-speed digital cameras were used with an eye toward collection of visual data. Stop-motion animation software was used as a vehicle for producing and sharing resultant external representations that students could create based on their observations. As will be discussed in subsequent sections, the former is already in use by professional scientists and the latter holds a great deal of promise as an accessible yet generative technology for student expression of their ideas.

The work to be described was driven by two major questions. These questions focused on issues of learning activity design and on the evaluation of a design. They included:

1. How can the combination of slow-motion video and stop-motion animation be co-deployed to encourage the production of more accurate and communicative visual models?
2. To what extent do elementary students improve in their depiction of complex movement phenomena as a result of using these co-deployed technologies?

The domain of emphasis was biomechanics. As will be discussed below, this is a topic that has had limited inquiry in science education research. However, it has great potential as a domain in that body experience and body data can both be leveraged in service of learning.

Biomechanics as a Domain for Science Learning

Generally speaking, biomechanics can be understood as the study of movement and displacement associated with biological systems and organisms. While research in biomechanics covers mechanical systems across a range of organisms, the studies that often generate the popular interest are those that focus on the human body. Part of the interest can be attributed to the applicability of biomechanics research to improved performance in popular sports (e.g., Barbosa et al. 2010). Part of it can also be attributed to the perceived personal relevance for individuals participating in their own personal health and wellness practices. For example, long-distance running is a common athletic activity for many active adults. It has developed into a complex social practice laden with its own specialized lexicons, rituals, and technologies (Lee and Drake 2013a). Within the larger adult running community, a debate has arisen related to the merits or risks associated with barefoot running. This debate involves arguments that humans evolved to run long distances without footwear for the purposes of survival on the one hand, and that humans actually need and improve their running and their safety with the use of specialized footwear on the other (McDougall 2009). The issue of which is the best way for humans to run (with or without shoes) is still unresolved.

To illustrate how this debate has escalated, consider that a study by Lieberman et al. (2010) published in the widely known research journal, *Nature*. This particular study examined how the human foot strikes the ground differently when a runner is or is not wearing shoes, and it lends support to the idea that barefoot running changes the biomechanics of the foot relative to shoe-based running. It also suggests that in certain conditions, barefoot running can be safe and appropriate for humans. This study has since been cited a number of times in popular media. In addition to demonstrating the degree to which biomechanics research has attracted popular attention and academic scrutiny, studies such as this are also instructive with respect to some of the scientific practices associated with this form of research. Specifically, it is common practice for such research teams like this one to engage in scientific modeling by using sophisticated motion-capture techniques (e.g., high-speed photography) coupled with mathematical analyses and computer simulations. By working to re-construct and re-represent the motions, the researchers ultimately come to a more systematic understanding of human body movement and locomotion. Ultimately, work like this demonstrates that biomechanics may have pedagogical promise, as it involves real science content, is familiar and relevant to anyone who has experience running, uses accessible technologies, and is organized around scientific practices such as modeling.

Yet, in spite of its promise, biomechanics of human movement has had a limited presence in research-based science education interventions, relative to other science topics (such as ecological systems or kinetic molecular theory). Still, there have been some noteworthy efforts to support teaching and learning of biomechanics content or to use it as a context to engage in forms of scientific inquiry, and those are summarized here.

One such pedagogical design effort came out of collaborative work stemming from the VaNTH partnership between Vanderbilt, Northwestern, University of Texas, and the Harvard/MIT Health Science Division. In that project, the goal was to integrate new learning technologies and designs for learning activities in the domain of bioengineering. Of note are the efforts to redesign undergraduate courses in the specific sub-area of human biomechanics (e.g., Roselli and Brophy 2003). As described, the instructional redesign process was deliberately based on learning principles identified in the National Research Council (1999) report *How People Learn*. Through active collaboration between biomechanics instructors and learning scientists, the biomechanics course moved away from a standard university lecture and recitation format and instead became one that involved "challenge-based instruction". Challenge-based instruction involves leveraging familiarity and interest in specific topics and presenting those in the form of tasks where students needed to generate their own conclusions given a range of available resources and tools. VaNTH was also informed by a "legacy cycle" activity sequence framework (Barr et al. 2005; Schwartz et al. 1999) that cycled students through a process of generating ideas, obtaining multiple perspectives, conducting research, running tests, and then making findings public before then repeating the entire cycle with a new set of challenges. For example, one biomechanics challenge developed through the VaNTH partnership involved students determining how much muscle strength was required to hold the "iron cross" position. The iron cross is a challenging, but common and easily recognized position in competitive men's gymnastics. Proper execution involves a gymnast using his hands to hold on to two hanging rings such that his body is orthogonal to the plane of the floor, while his arms are extended and parallel to the floor plane. When this position is held, the body takes the shape of a cross.

As the students worked on analyzing the hold, they received video-recorded testimonials about the iron cross from a surgeon, mechanical engineer, a sports physical therapist, and engineering graduate student to help them understand the problem from multiple perspectives. Then, students examined computer visualizations and analyzed anthropometric data of the shoulder joint, which then led to a generalized formulation of how the shoulder joint worked and how much strength was required from the various muscles involved. Other biomechanics challenges emerging from the VaNTH collaboration included students' analyses of gait, ground forces while walking, and jumping jacks. This overall approach of instructional design and technology use has been successful, as reflected in tests that examined student affect, conceptual test scores, and measures of adaptive expertise (Pandy et al. 2004).

A comparable and related effort was also undertaken with secondary school science classrooms. Klein and Sherwood (2005) reported on a study that also used the legacy cycle and challenge model to introduce bioengineering content in high school classrooms. Their aim was to see whether secondary schools could use a range of bioengineering tasks as meaningful anchored instruction contexts for learning biology and physics. This effort also emphasized biomechanics in several learning modules, including the aforementioned module about the iron cross in addition to modules on swimming and on balance. Comparisons of performance on a variety of assessments also showed significantly greater improvements in a number of content areas and on application problems relative to control classrooms that used more traditional instruction.

Looking to even younger students, biomechanics as a content emphasis has actually also been attempted with students in third and fourth grade (Penner et al. 1997, 1998). In these classroom design experiments, the elementary students were involved in a number of modeling activities, including designing and modifying physical models of the human elbow joint and exploring torque and levers as they relate to the biomechanics of the elbow. The students in these studies served as a powerful demonstration case of the modeling capabilities of elementary students in a properly supportive learning environment and with appropriately designed learning activities. One key finding was the overall improvement in the design of students' physical models as they became more aware of important structures and motions associated with the elbow coupled with a decrease in the amount of attention dedicated to superficial features (e.g., objects that simply have the shape of elbows). Indeed, this design experiment is among those that informed much of the most recent discussion and advocacy for modeling activities in elementary science classes (Duschl et al. 2007).

Building on that latter instance of successful elementary biomechanics instruction, the overarching goal of this project has been to devise a way to improve some of the fundamentals associated with students modeling capabilities. The theoretical perspective that informed our effort is based in the idea that children possess rich pools of metarepresentational competence (diSessa 2004). This perspective basically posits that children draw from a set of intuitive resources that enable them to create and critique representations (e.g., Azevedo 2000; diSessa et al. 1991; Elby 2000) and that these must be tapped in order for a student become facile in their use of representations in science (diSessa 2004). Many of these resources are based in very familiar prior experiences, even tracing back to the basic and frequent childhood activity of freehand drawing

(Sherin 2000), and thus, they can be elicited in the context of activities that bear some initial resemblance to those that are already familiar. While evidence is accumulating that these metarepresentational resources do indeed exist (e.g., Verschaffel et al. 2010), their productive utilization in classroom instruction is ultimately contingent upon the careful design and enactment of learning activities that both require students to access these resources and provide means to publicly recognize and sanction these resources in the midst of classroom activities (Azevedo et al. 2012; Danish and Enyedy 2006; Enyedy 2005). What we hoped to offer through the pursuit of this particular project was an account of precisely how existing image capture technologies could be used in conjunction with a content emphasis of human body movement to encourage students to improve in their representational capabilities.

Technology Supports for Modeling Movement

As with some of the other articles in this special issue, the perspective maintained in this work is that existing technologies can support innovative teaching and learning activities. For the current project, two separate, low-threshold commercial technologies were co-deployed, so that they could together support students in both inspecting observational records and creating representations of human body movement. This was done through a set of activities organized around the espoused goal of producing realistic animations of movement. The first technology was slow-motion video obtained from high-speed cameras. While it is true that any video can be played back in slow motion, high-quality slow-motion video (of the caliber used in professional sporting events and in biomechanics research) must be recorded with a camera capable of capturing images at much higher speeds than a standard consumer camera. Typically, consumer cameras with video capabilities record at around 30 frames per second (fps). This means that in a single second, 30 images that comprise the animation are captured and stored. High-speed cameras are specially equipped such that they can capture many more frames per second, and thus, the video that is recorded has much sharper images for each fraction of a second, as the exposure time is reduced (reducing blur for each frame). When the high-speed recorded video is played back at the typical play rate of 30 fps, the result is a high-resolution video that appears to depict highly detailed movement in slow motion.

As observed earlier, such video technology has already proven to be an important tool in professional scientific research. High-speed cameras and the resulting slow-motion footage they produce have been used in recent years to better understand negative ground flashes associated with lightning (Ballarotti et al. 2005), the dynamic formation of drops and bubbles in fluids (Thoroddsen et al. 2008), and even how cats' tongues are used to support fluid uptake (Reis et al. 2010). In all of these studies, slow-motion video footage is acknowledged specifically, and the reported data analysis processes involve researchers reviewing footage iteratively in order to support the building of mathematical or visual models that can best represent the behavior of interest.

Previous work with slow-motion video in educational settings has typically involved the use of specialized video analysis software and digitally tracing motions over discrete images (e.g., Boyd and Rubin 1996; Koleza and Pappas 2008). The results obtained in such environments have been noteworthy, in that students from those studies were able to improve either in their abilities to generate visual models of motion paths or in their content understanding of science topics such as position and velocity. For the current work, we opted to simply use off-the-shelf cameras and native video playback tools already installed on classroom computers. To facilitate the selection and use of off-the-shelf cameras, we consulted with a biomechanics professor at a major research university who was actively conducting research on human movement. Given this expert's high-speed camera recommendations and, after careful research and testing, we ultimately purchased Casio Exilim EX-ZR200 cameras to use in this project. While these are promoted as point-and-click digital cameras, this line of Casio cameras is fairly unique in that they have high-speed video recording capabilities of up to 1,000 fps. However, one trade-off with increasing the fps is that the height and width of the recorded footage are necessarily reduced. The other related trade-off is that the higher the fps, the larger the resulting video file is for the same amount of recorded time. Ultimately, this limits the amount of activity that can be recorded at a time. As such, we often had students work with video recording at 240 fps, which is fewer than what is done in professional biomechanics research but still high enough quality (and slow enough resulting playback footage by roughly tenfold) for our purposes.

The second technology we used was stop-motion animation software. Specifically, we used the SAM software developed out of Tufts University (Searl et al. 2009) and distributed through *iCreateToEducate*. The SAM software makes it possible for students to create animated stories through repeated capture of still images from either the webcam already built into their computer or with an attached external camera.

As described by Gravel (2009), there were a number of pedagogical design principles involved in the initial conceptualization of the SAM software, but important among these was the framework of constructionism, pioneered by Papert (1980). Briefly, constructionism is based on the Piagetian theory of constructivism that posits the development of new knowledge structures from existing ones,

Table 1 Summary of designed unit and activity sets

Activity series	Description	Number of class periods
Unit introduction	Students shared and discussed their prior knowledge about how animations are made. Instructor presents overview and examples of early animation techniques. Students imitate some to complete first set of flipbooks to depict movement (pre-assessment)	2
Modeling a Bouncing Ball	Students were introduced to SAM animation software and its functionality. Pairs or groups of students use construction paper to create an animation of a bouncing ball. Animations are presented and discussed in class, followed by presentation of slow-motion video footage of actual ball bounces. Groups of students work to create a new bouncing ball animation with new, non-paper materials. These are shared and discussed in class again	4
Modeling a human vertical jump	Student volunteers are recorded while performing a jump in front of a high-speed camera. Footage is reviewed and discussed in class, and then pairs of students proceed to create animations using another new set of depictive materials that show the vertical jump. The jump videos are shared and discussed in class	3
Making an animation with two student body movements	Each student is recorded with a high-speed camera performing a movement of their choosing. Pairs are given footage of their movements and must work together to create a short animated story that incorporates both students' movements using yet another set of new depictive materials. Final combined animated stories are shown to the entire class	3
Final assessment	Students draw a final set of flipbooks depicting movement (post-assessment)	1

but then "adds the idea that this happens especially felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe." (p. x, Papert 1991). In this case, the constructed item is a short animated movie created by a student who may otherwise not have opportunities to create their own dynamic representations of phenomena. Research and development efforts that use SAM to support learning of science are currently ongoing. For example, SAM software has been adapted to support students' in work relevant to the modeling of molecular interactions (Wilkerson-Jerde et al. 2014).

Our approach in using SAM software was to support students' visual modeling of human body motion. We had hypothesized that the combination of both slow-motion video and stop-action movie making software would enable and encourage students to carefully inspect, reflect upon, and represent important aspects of otherwise familiar body movement. The slow-motion video would provide students with much more time to notice what parts of the human body were moving at what time and also provide an anchor for small group and classroom discussions. The animation software would encourage students to negotiate what they should include in a new, real-time depiction of the same motion through different depictive media (e.g., Wilkerson-Jerde et al. 2014). While the scientific practice of modeling encompasses several other cognitive activities, epistemic commitments, and social interactions (Louca and Zacharia 2011; Schwarz et al. 2009; Windschitl et al. 2008), these dual processes of interpretation and translation into alternate media were ones we saw as core to modeling and ones that could be well supported through this combination of technologies.

Classroom Activity Design

This design endeavor was undertaken under the auspices of a larger series of classroom design experiments (e.g., Brown 1992) that helped students work with new technologies, so that children could obtain and analyze data about their physical activities in order to support development of refined data analysis competences. Many of our team's prior efforts have involved use of quantified data, such as heart rate over time or footsteps during recess (Lee and Thomas 2011; Lee and Drake 2013b). However, and as described above, visual data—in the form of video footage of motion—can and do play a critical role in professional biomechanical scientific inquiry as well. As such, we sought to expand our overarching research and design focus to also include visual records of physical activity.

To support students in productively working with visual records, we designed and implemented a unit enacted over 13 days with a set of fifth graders from a local partnering elementary school in the Mountain West region of the USA. Due to existing school schedule constraints, this unit took place during the last few weeks of their academic school year. The theme of the unit was presented as "animation," and it was offered as a special elective option for the students in two-fifth grade classes who were provided with a series of options for short units related to

STEM activities, such as basic computer programming, robotics, or circuits and soldering. As is sometimes the case with classroom design experiments, the research team both helped facilitate and support the unit along with the classroom teacher, given the research team's greater familiarity with the technologies and content being covered. The researchers freely interacted with the students, led some of the learning activities, and posed questions directly to the students during the unit. In total, we had 15 students participate in the unit.[1]

The resulting unit was organized as a set of four activity series (Table 1). The first series involved an instructor-led overview of animation and how it had historically been produced by hand as a series of still frames on transparent cells prior to the advent of computer animation techniques. This introduction involved viewing and discussing classic animated videos and cartoons and discussing what artists had to do to create the appearance of motion. Following that introduction, each student was tasked with the creation and public sharing of two paper-based flipbooks. They were asked to make the animations in their flipbooks as realistic as possible and to use similar techniques to those done by professional animators (i.e., repeated images). As discussed below, these flipbooks served as a pre-assessment of the students' motion depiction capabilities. The flipbooks were completed individually during a single class period.

The second series of activities involved introducing the SAM software and then providing class time for students to use SAM to depict the bouncing of a ball. While the focus of the unit was human body movement, the decision was made to begin with a much simpler motion with less moving parts, as students were first familiarizing themselves with the SAM software. Students worked in teacher-assigned pairs or groups of three to take a circle of construction paper and use it to depict, by way of repeated still images, what they believed would be a realistic illustration of the bouncing motion based on their prior informal experiences with bouncing balls. This was then followed by a public showing of their first animation efforts to the rest of the class, and then a class discussion about what did and did not seem realistic about each group's movie. The students then were posed with the question of what kinds of information they would need in order to produce more realistic animations, which then led to the introduction of the high-speed cameras as a tool to provide them with inspectable records of actual ball bounces. The students were next given the opportunity to view slow-motion videos of different sized balls that were being dropped that then subsequently bounced. The use of different sized balls and multiple instances was intentional to encourage students to attend to commonalities associated with the motion rather than idiosyncrasies associated with a given video record. The class then discussed what was common across the different recorded situations. Students then returned to their pairs or small groups to re-create the ball drop animations again with the SAM software.

At this point, we also introduced a change in what the students could use in their animations. Because part of modeling involves students creating representations that have their inherent advantages and limitations based on properties associated with the depictive media and research on metarepresentational competence suggests such knowledge is abundant, we opted to set up this second effort at creating a SAM animation in a manner that would encourage students to explore some of those trade-offs. Specifically, we did this by changing what materials students had available to use in their animations after their first animation session. For the re-creation of the ball drop, students were given a range of objects to use (such as tissue paper, rubber bands, paper clips, and post it notes). The goal here was to encourage students to focus on depicting the motion, rather than superficial features of the situation being modeled (such as the color of the ball) and to seed discussion of affordances and limitations associated with each medium. The new ball bouncing videos were then publicly shared and discussed.

Following the two iterations of bouncing ball animation, the third series of activities involved students exploring how they could animate a human being jumping as high as they could. This led to students volunteering to be recorded with the high-speed cameras as they jumped as high as they could while in the school cafeteria.[2] After these slow-motion videos were obtained, they were provided on individual computers for student groups to review together and compare across multiple jumping students, so that they could then depict the jumps in the SAM animation software. A new set of depictive materials was provided and randomly selected by students, with the restriction that students were to use only the materials set that they had drawn from a random material selection process. Student groups worked either with string, beads, aluminum foil, tangrams, clay, colored construction paper, pipe cleaners, or with a posable artist's mannequin.[3] Again, when these new animations were completed, they were shared and discussed in the class, with the topic of discussion being what made the motions look more or less realistic.

[1] Of the fifteen students, one had some special needs and was allowed to opt out of any assessment-related work for this unit. He is not represented in the assessment results described in the latter parts of this article. However, this student's contributions to class activities were recorded and stored on research video with appropriate consent.

[2] The cafeteria had better lighting and more room for students to gather and observe what was being recorded.

[3] The artist's mannequin was initially seen by students as an easy and desirable object to use because it had the shape of a person. However, the students soon discovered that it had some major movement and position limitations and was difficult to use for the kinds of two-dimensional animations they were creating.

Table 2 Coding scheme for evaluating student flipbooks

Coded attribute	Description
Epistemic fidelity: phases	Standing Jumps can be understood as consisting of four phases
Approach	Initial preparation phase for the jump. Begins with jumper standing. Coded as present if the "jumper" made some downward, bending movement prior to jumping
Takeoff	The transition from ground to movement in the air. Begins with the jumper in crouched position. Ends when the jumper's feet leave the ground. Coded as present if the "jumper" showed some intentional body straightening before leaving the "ground"
Flight	Arms continue upward until the hands are above the head. As the body comes back down, the arms also lower. Ends when the jumper's feet touch the ground
	Coded as present if the "jumper" left the "ground"
Landing	Begins when the jumper's feet touch the ground
	The feet flatten out (ankles are dorsiflexed), the knees are flexed, the hips are flexed. The hips then straighten, the knees straighten. Coded as present if the "jumper" does more than simply touch down
Epistemic fidelity: limbs	In addition to different phases, there are also important movements associated with limb movements such as arm and leg position and angles that aid in the jump because of their role in maintaining balance or creating a 'spring'-like quality in the jump. Some of these limb movements can span across phases and thus were coded separately
Approach phase limb movements	The hips and knees flex, the arms move back, (ankles are dorsiflexed, meaning the angle between feet and legs is decreased). Coded as present if legs bend and arms swing backward during Approach phase
Take-off phase limb movements	Hips are extended (straightened), knees extend, feet point down (ankles are plantar flexed), arms move forward. Coded as present if knees extend, and if arms had moved backward, then are brought forward during the Take-off phase
Flight phase limb movements I	Arms extend upward during flight ascension. Legs have already been extended during Takeoff or are continuing to extend in the drawings. Coded as present when intentional arm movements that rose to shoulder level or above during Flight phase
Flight phase limb movements II	Arms lower during flight descension and/or when landing. Coded as present when raised arms are lowered to or below chest level during descension in Flight or Landing phases
Landing phase limb movements I	Legs bend during beginning of landing. Coded as present when leg bends appear during the Landing phase
Landing phase limb movements II	Legs straighten during end of landing. Coded as present if legs are straightened or are straight at the end of the Landing phase
Consistency	These qualities refer to consistency with respect to what is likely physically and also to maintaining consistency with the initial conditions provided by the starting stick figure
Consistent body size	Coded if the "Jumper" stays approximately the same size throughout the animation. Slight deviations due to imprecise drawing error are acceptable
Consistent viewing perspective	Coded if the "Jumper" is depicted as facing sideways through the whole movement, rather than changing to forward or backward facing as is the norm for stick figure drawings. Changes in perspective after the jump completion were not considered
Scale of jump distance	Coded if the height of the jump is appropriate for the height of the "jumper," roughly estimated as no higher than a half body length for a vertical jump or at most a full body length for a horizontal jump
Limb angularity	Coded if the "Jumper's" limbs move within acceptable angular ranges given normal joint limitations
Conventionality	Relative to animations and drawn biomechanics models
Smooth animation	The animation is smooth and is spread across multiple frames (sheets)
Lack of spontaneous objects	Only the "jumper" is included. No extraneous objects (e.g., basketballs, sharks) are added

The final series of activities involved every student choosing their own unique body movement to record with the high-speed cameras. For example, some students chose to record themselves doing backflips, swim strokes, or even pretending to stumble and fall. The students were then assigned new partners and given the task of creating a story that incorporated both of their uniquely recorded movements. The student groups were each permitted to use any of the materials available. The final videos were then compiled and aired during a parent and community showcase of the various projects that students throughout the school completed related to STEM content. Following this final activity set, the students met 1 week after the unit had finished and had one class period to again individually complete one more set of flipbooks that were identical to what they were asked to complete at the beginning of the unit, which served as a post-assessment for the unit.

Data Sources

We obtained three forms of data during this unit. First was video footage of every day of the animation unit. This video came from a manned high-definition video camera that was located in the back of the classroom on days that involved whole class discussions and then was selectively focused on student groups during small group animation production days. Second, we obtained copies of all the animation files that students had created in the SAM software, which consisted of hundreds of still images from the different animation projects. Third, we collected and kept the original flipbooks that students had made on the first days of the animation unit and then also asked them to prepare a new set of identical flipbooks on a final day when the unit was completed. While all three sets of data were important for our records (e.g., Yuan, et al. 2014), the flipbooks are a central focus for the current article.

The flipbooks were prepared specifically so that we could use those as a tool for us to get some sense of students' ability to represent body movement before and after the animation unit. Each flipbook was designed such that it had the same stick figure character on the first page. The students were tasked with creating two different flipbooks at the beginning and the end of the unit during a single class period (for a total of four flipbooks per student). The first involved showing the stick figure jumping as high as it could (a vertical jump). The second involved showing the stick figure jumping as far forward as it could (a horizontal jump). The vertical jump, which is a common example in biomechanics textbooks, was selected as a familiar topic that students would definitely encounter during the unit. This modeling task would let us determine whether students improved in their ability to show human body motions that they spent time examining in the unit. The horizontal jump was a form of "near transfer" assessment task to help us examine how situation-specific students' understandings of the jumping motion was. We had suspected that students could be sufficiently familiar with the vertical jump task to apply many of the same ideas to the second flipbook, but could also default to a simplified and biomechanically inaccurate depiction because the movement was not one of the specific ones they would work with during the unit.

Flipbook Analysis

While drawings have a long tradition in science assessment tasks, the analysis of flipbook animations is not nearly as well traversed a territory. Knowing this, we felt that we needed to develop an analytical scheme suited to our specific needs that could also potentially be useful for others who might consider flipbooks as an assessment instrument.

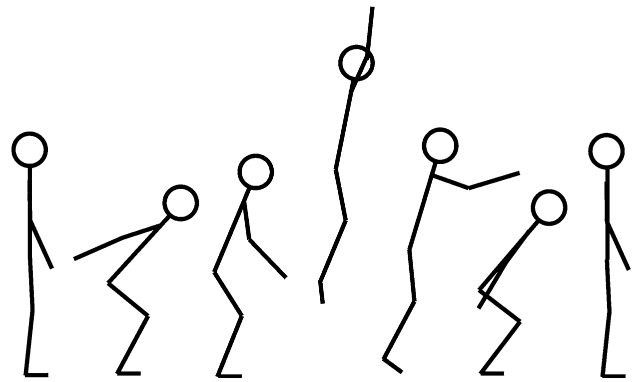

Fig. 1 Canonical sequential depiction of the body and limp positions and phases associated with a vertical jump from a standing position

We began with a grounded approach, reviewing the contents of the flipbooks immediately after the first set of flipbooks was completed at the beginning of the unit. Commonalities across these flipbooks (such as stick figures changing vertical position or stick figures shrinking over time) were identified as features for us to evaluate. In addition to identifying features associated with these particular students' flipbooks, we again referred to the literature related to students' metarepresentational competence (e.g., diSessa 2004; Sherin 2000; Verschaffel et al. 2010). One tool that was of great use to us was a coding scheme developed by diSessa (2002) that identified some criteria by which students critically evaluate student-drawn representations. Among those criteria were judgments associated with epistemic fidelity (i.e., were the depictions accurate with respect to what they were representing), consistency (i.e., depictions in the representation maintained similarities over time and were not changed abruptly), and conventionality (i.e., were some tacit conventions of frame-based motion depiction observed, such as maintaining smoothness between frames to produce a more fluid animation).

Our resulting evaluation rubric contained 16 components associated with the aforementioned three clusters of representational criteria (Table 2). Ten components were pertained to epistemic fidelity and were developed by comparing against established models of jumping from college-level biomechanics textbooks (i.e., Alexander 1992; McGinnis 2013) and from additional review by an individual with graduate-level training in biomechanics. Of those ten, four were associated with common phases of a jump (approach, takeoff, flight, and landing), and the other six were limb movements that take place during those phases (Fig. 1). There were also four separate consistency components that were selected based on deviations of students' initial flipbooks from canonical animated depictions of jumping biomechanics. The final two components

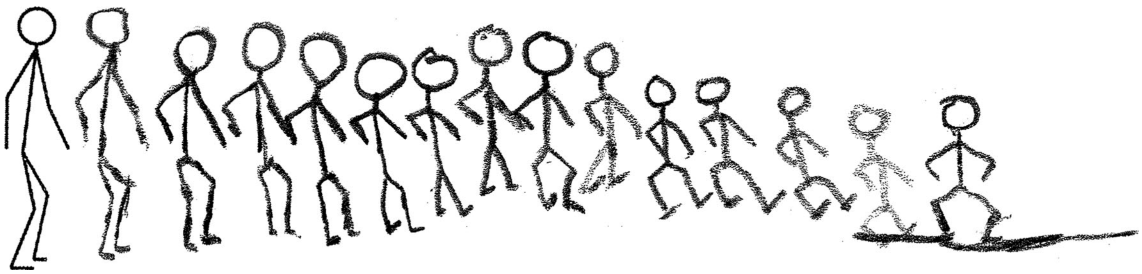

Fig. 2 Ivan's flipbook animation of the vertical jump at the beginning of the unit, compiled into a series of sequential images

in the rubric also were based on unexpected deviations from canonical animations; namely, some students made what looked like very disjointed animations with figures and positions changing abruptly from one page to the next and others included objects or items that were unnecessary and fleeting. While they all were familiar with and able to perform vertical jumps, their ability to represent that movement accurately appeared to be initially quite limited (e.g., Figure 2).

In the rubric, each component could receive one point based on its presence. Partial or ambiguous inclusion of a component would receive a half point. Lack of a component or major discrepancies relative to the component received zero points. A total score was computed by summing the component scores, with 16 points being a maximum possible value.

To test the reliability of this assessment rubric, two analysts independently scored a random sample of six flipbooks. The independent scoring of the sixteen components across this sample exhibited high reliability ($\kappa = 0.96$).[4] The remainder of the corpus was scored individually by just one of the two analysts.

Results and Observations

Flipbook Scores

On the flipbooks completed at the beginning of the unit, the students averaged a score of 7.39 (SD $= 2.96$, $N = 14$) for their flipbooks that depicted the vertical jump. These flipbooks were often limited in their accuracy in that several of them appeared to be little more than a vertical translation of the stick figure, despite students' own personal bodily familiarity with vertical jumping. Students averaged a score of 2.64 (SD $= 0.93$, $N = 14$) for the jump phases, 1.85 (SD $= 1.49$, $N = 14$) for the limb movements, 1.25 (SD $= 1.01$, $N = 14$) for consistency, and 1.64 (SD $= 0.63$, $N = 14$) for conventionality. This breakdown suggests that students had the most difficulty with maintaining epistemic fidelity, with respect to the four jump phases and the movement of limbs. This is illustrated by the pre-unit vertical jump flipbook that Ivan created (Fig. 2). Other errors common in the students' flipbooks that affected their consistency were a size reduction (i.e., their jumper shrank over time) and a gradual shift toward more canonical "front-view" depictions of a stick figure. The cause of the former error is unknown, but could have been from lack of attention to the size of preceding pages of jumpers or students trying to reduce the amount of drawing they needed to do by making the jumper smaller. The tendency to change the side-facing jumper into a front-view stick figure drawing may be attributable to the tendency for children, noted in developmental psychology research, to encode and represent drawn figures with standardized shape drawing routines (Karmiloff-Smith 1990). Stated another way, we learn from an early age to draw people as front-facing stick figures and will often revert to that until we progress in both our knowledge of the object being depicted and in our representational abilities.

The scored pre-unit flipbooks showing a horizontal jump averaged a score of 7.50 (SD $= 1.76$, $N = 13$).[5] The breakdown by subcategory was an average of 2.92 (SD $= 0.95$, $N = 13$) for the jump phases, 0.11 (SD $= 0.21$, $N = 13$) for limb movements, 1.54 (SD $= 0.72$, $N = 13$) for consistency, and 1.73 (SD $= 0.44$, $N = 13$) for conventionality. Like the vertical jump drawings, the animations often consisted of translation of the same or highly similar figures with no change to limbs or body angles. As shown in an example from a student, Keisha,[6] (Fig. 3) repeating the same-sized and shaped image was a challenge on this task as well. There was again the default use of the standard "front-facing" stick figure. The overall scores on the pre-unit vertical and horizontal jump flipbooks did not differ significantly ($p = 0.9$).

After the unit, there was a clear difference in the quality of the vertical and horizontal jump flipbooks. The mean

[4] Initially, we had 17 components with one related to maintaining consistent proportions across the flipbook. The agreement on this component was low (33 % agreement), so this was eliminated.

[5] One student needed to leave class prior to completion of a second flipbook depicting the horizontal jump, and thus had unmatched data and was excluded from this analysis.

[6] All proper names are pseudonyms.

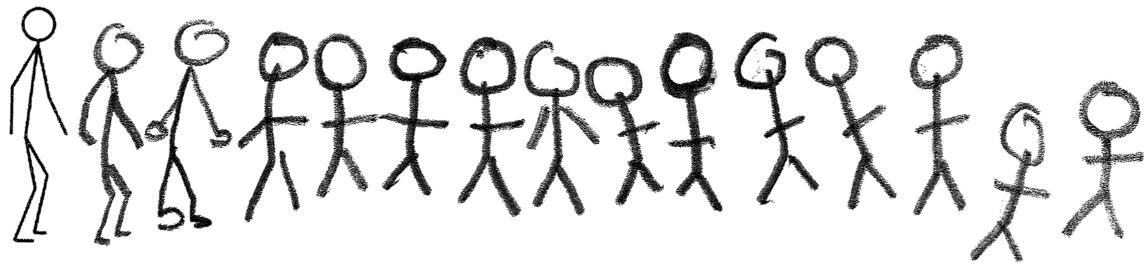

Fig. 3 Keisha's flipbook animation of the horizontal jump at the beginning of the unit, compiled into a series of sequential images

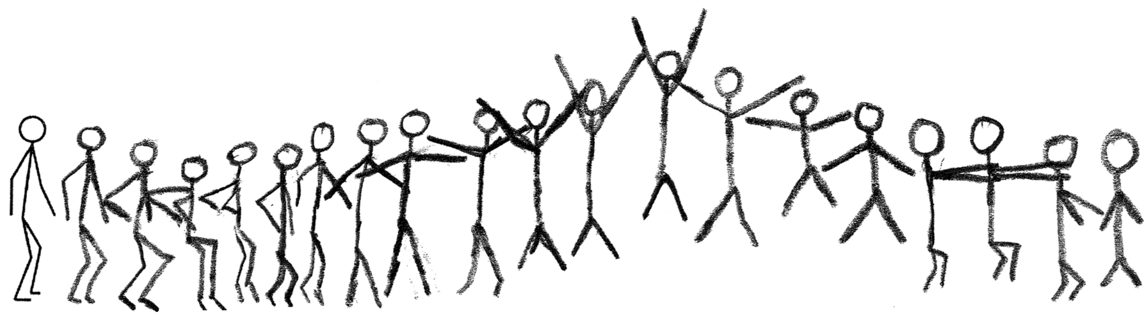

Fig. 4 Ivan's flipbook animation of the vertical jump at the end of the unit, compiled into a series of sequential images

score for the post-unit vertical jump was 12.79 (SD = 1.73, $N = 14$). This was a significant improvement over the pre-unit flipbooks, as determined by a paired t test ($t = -6.8718$, df = 13, $p < 0.001$). There was a significant improvement in all subcategories except for conventionality ($p = 0.19$). Figure 4 serves to illustrate how Ivan's flipbook had improved after he had completed the unit. In his post-unit vertical jump flipbook, Ivan showed all four phases of the jump and more actively involved limb movements including bent elbows, knees, and, during the takeoff and beginning of flight, the ankles. It is worth noting that during the flight phase, Ivan defaulted to the front-facing stick figure shape, which represented a change in perspective. However, he proceeded to show a more accurate landing phase with the original orientation. Unlike his pre-unit flipbook, he also maintained a stick figure of roughly the same size as the one he started with, which helped produce a much smoother animation.

The average score on the post-unit flipbooks for the horizontal jump was 10.48 (SD = 3.20 $N = 13$). This also was a significant improvement over the pre-unit horizontal jump flipbooks as determined by a paired t test ($t = -3.6841$, df = 12, $p < 0.01$). For the horizontal jump, significant improvement appeared in both areas of epistemic fidelity ($p < 0.01$ for both), but not in consistency ($p = 0.35$) nor in conventionality ($p = 0.81$). There were no significant differences in consistency ($p = 0.45$) or conventionality ($p = 0.75$) between the post-unit horizontal jump flipbooks and the vertical jump flipbooks. The differences between the two types of jump with respect to jump phases and limb movement were significant ($t = 3.5418$, df = 12, $p < 0.01$; $t = 2.57$, df = 12, $p < 0.05$, respectively) with the vertical jump having a higher average in both. This suggests that students were able to draw on some specific aspects of body positions and phases associated with the vertical jump when tasked with the horizontal jump, but not all.

While the final scores were not as high in the horizontal jumps, the improvements in the horizontal jumps were easy to discern through qualitative examination. Keisha's post-unit horizontal jump flipbook (Fig. 5) demonstrated improvement in that it showed all four jump phases, maintained consistent perspective, and included continuous and fluid limb movements (albeit with some embellishments, such as added hand shapes, and slight changes in character size).

Observed Classroom Experiences

Based on the scores assigned to the students' pre- and post-unit flipbooks, it appeared that this designed unit had some positive effect on their ability to represent, by way of animation, some human movement. The selection of technologies and the sequence of activities were intentionally made to support such improvement. Yet what was the nature of the specific experiences that students had during the unit to bring about these changes? A comprehensive answer is beyond the scope of this paper, but we present below two brief examples involving the two students whose flipbooks were shown above (Keisha and

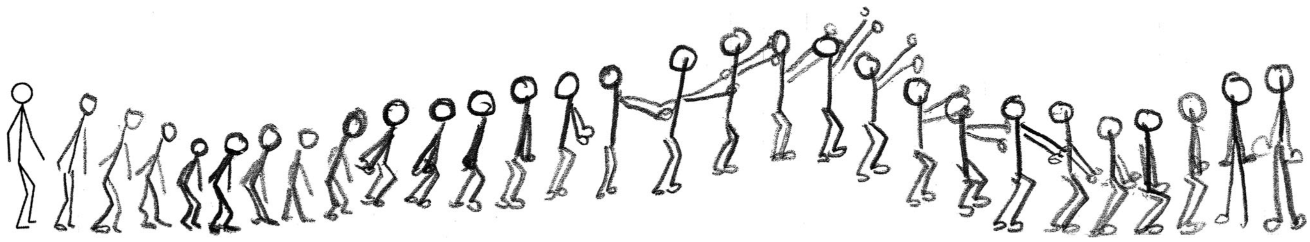

Fig. 5 Keisha's flipbook animation of the horizontal jump at the end of the unit, compiled into a series of sequential images

Ivan) that we noted from our observational records of classroom activity.

The first example involves Keisha and is presented by way of a brief excerpt from the first series of SAM animation activities (modeling a bouncing ball). This particular excerpt took place in class after the entire group of students began viewing the slow-motion live action ball bounce videos. Immediately after viewing them, there was an immediate disagreement as to when the ball was going fastest. Keisha volunteered that she thought the ball was going faster the more that it bounced. However, and as illustrated below, the assertion itself was not deemed sufficient as a justified claim.[7] The following conversation, which took place during a class discussion, involved students being pressed by the teacher for strategies they could pursue to provide evidence to justify the claim that the ball was faster as continued to bounce. It serves to illustrate students' engagement with and thoughtful consideration of motion phenomena they were to model.

Instructor	So Keisha thinks [the ball] gets faster with the later bounces. How can we tell? … Say Ms. Williams [a student teacher working at the school] doesn't believe us. How can we convince her that it does that?
Tara	*(Tara uses her hand to gestures the ball bouncing motion over her desk)* We would count this is 1 s, *(her hand hits the desk, then she gestures a second, shorter bouncing motion and hits the desk again)* this is a half a second
Instructor	So with every bounce, count how many seconds it takes?
Keisha	But it [the height of the ball] gets lower. *(Keisha uses her hand to gesture the ball bouncing motion in front of her, with the height of her hand decreasing after each bounce)* If you time each count, as it gets lower it would be less time [between bounces] so it wouldn't work
Tara	That is what I am saying
Keisha	It will always be different
Tara	*(Tara gestures the same ball bouncing motion as she did earlier, pausing at each apex)* It would be slower because this one goes up higher and then goes bounce
	Instructor asks if anyone else in the class can comment on this disagreement and then calls on Emma
Emma	It is kind of hard to explain how Tara's way would be. It can't necessarily work because what would happen is you would need a—you are recording the speed of the ball going up and down *(Emma gestures the ball motion up and down with her hands)* so you can't necessarily count how long it would take from the top to the bottom because once it bounces, it [the ball] doesn't go as high as it started. It [the height of the ball] gets lower. So you are going to have to record the speed of the ball each time it hits [the ground] instead of recording how long it takes to hit the ground

Briefly, Tara thought the decreasing amount of time between ball bounces would be evidence that the ball was moving faster. Keisha disagreed and thought that the fact that while the amount of time between each bounce of the ball was decreasing, they would not be able to infer speed because the distance was also changing. Emma concurred with this point as well. Altogether, this excerpt involving these three girls shows the ways that students, when given an appropriate prompt from the teacher, would reflect upon and attend to key aspects of the motion they could see in the slow-motion video footage. Similar instances of this kind of discussion took place in small groups throughout the unit.

The second example comes from Ivan's work during the final series of activities (modeling a unique movement the students had themselves performed and recorded on the high-speed cameras). Ivan was an avid soccer player and had opted to do a soccer kick as his unique body movement. Throughout the unit, he appeared to pursue all of the animation tasks halfheartedly and required reminders of how much time he had left during each lesson. (He often

[7] Indeed, the velocity of the ball decreases over time as the ball eventually comes to a stop. However, as Parnafes (2007) has noted, students' recognition of what is "fast" can involve attention to a number of visible aspects of an analyzed situation.

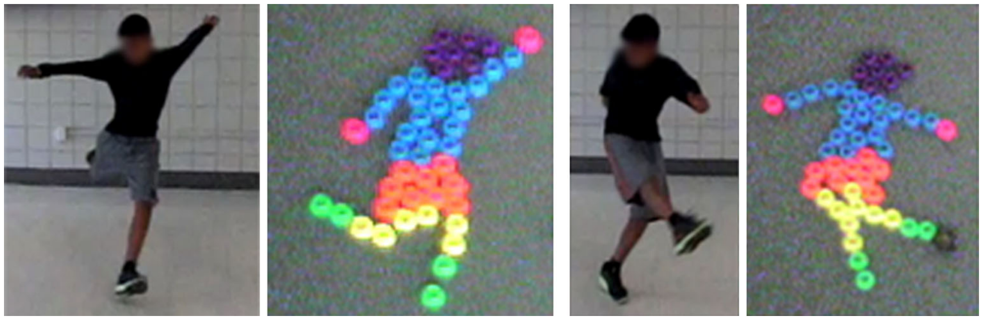

Fig. 6 Still images of Ivan's high-speed camera recorded soccer kick juxtaposed against still images from his SAM animation project. Note the similar positioning in several limbs

used much of his time with the SAM software as an opportunity to socialize with his friends.) For the final activity series, a project team member saw that Ivan's first efforts at modeling the kick were very simplistic. They involved using beads to make one leg on a crude human figure move sideways. The resulting animation looked nothing like the video that Ivan had recorded. When the instructor came to check on Ivan's progress and also saw that the video looked so different from Ivan's SAM animation, he highlighted the discrepancy to Ivan, who then expressed frustration since he felt he had adequately shown a kick. The teacher then suggested he just focus on one body part at a time and verbally describe what was changing. Ivan complied and then noticed how his hands were moving and how far back his leg was being pulled back in preparation of his kick. He then proceeded to redo his beads to better capture some of these movements and then redid them a third time, so that he could make it fit into an imagined scene he was producing with his partner (Fig. 6). While Ivan's and his partner's final product was not a full reproduction of what the recorded slow-motion video had shown, several aspects of his kick animation improved noticeably with the increased attention to various body parts.

Taken together, these two examples serve to illustrate two points. First is that the students can demonstrate sophistication in interpreting the phenomena to be modeled. These two examples showed how attentive students could be to the phenomena captured in the slow-motion video. The ability to look at such detailed video certainly supports that, as does the requirement to reproduce the movement in some way in a new representational medium. The second point is that while these moments can happen, it is important to recognize that a capable and involved teacher or facilitator still plays an absolutely critical role in the provision of just-in-time support for students to do such work. In the first example, the teacher pushed students to go beyond an assertion of how things were moving and to more carefully consider how they would analyze the movement in a more rigorous and empirically driven way. In the second example, the facilitator helped to highlight a discrepancy in what Ivan was modeling and what he had produced, and then helped direct Ivan's attention to a smaller subset of features that ultimately made it into his final animation. As is often the case in novel technology-enhanced learning experiences, the technology and activity design helped set the stage for students to make progress in modeling body movements, but the strategic and thoughtful participation of a more knowledgeable adult throughout the designed unit was integral as well.

Conclusions

In this paper, we sought to demonstrate how two technologies could be combined to support students' depictions of human movement, a topic with which students are intimately familiar tacitly but are not always familiar with explicitly. We described a classroom design experiment with a group of fifth-grade students that was organized around the theme of animation and contained a carefully considered series of activities that involved students reviewing slow-motion records and then re-representing motion. The design experiment placed students in the role of translators between two forms of dynamic representation and involved multiple cycles of creation, sharing, and critique. These are all key and initial aspects of the scientific practice of modeling, and as demonstrated in this article, can be effectively brought in at the elementary level (Achieve 2013; Schwarz et al. 2009).

Through analysis of flipbooks that students had created at the beginning and end of the unit, we were able to see that students improved significantly in their ability to represent familiar human movements. While they were already tacitly familiar with the movements, they were not yet as skilled at representing those movements. Through two brief examples taken from classroom observations, we discussed how the participating students, with proper support from the teacher, could engage productively with the slow-motion videos with which they were provided and then convert those visual data into new representations. Given those initial results and observations, we believe that the proposed approach for combining the technologies is a promising one. Moreover, they resemble some of the dynamic modeling activities that also already take place in professional scientific practice.

However, this was a single intervention with a small group of students that had a great deal of support from a research team. More work in the future would be needed to further test this approach and also to determine the best ways to deploy the selected technologies in support of more sustained modeling. Furthermore, because of timing (this unit was done at the end of the school year and faced typical classroom scheduling constraints), we were unable to explore any changes in the epistemic dimensions of modeling. Throughout the unit, students were directly involved in creating and refining dynamic visual models, but we cannot say whether or not students recognized these acts of creation and refinement as inherently part of scientific modeling. Also, we organized the unit around the theme of animation, which could also complicate the extent to which students explicitly thought of these creation and refinement processes as being part of a practice that we as science educators call scientific modeling. However, it is worth noting that there is an established tradition in science education research that has demonstrated that people of all ages can be seen as both knowing and doing science without explicit realization that what they do or know counts as science (Bell et al. 2009; Steinkuehler and Duncan 2008). At a minimum, we believe that this current study provides another case to the literature of what students can learn and do that is of relevance to the knowing and doing of science.

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References

Abrahamson D (2009) Embodied design: constructing means for constructing meaning. Educ Stud Math 70(1):27–47. doi:10.1007/s10649-008-9137-1

Achieve Inc (2013) Next generation science standards. Achieve, Inc., Washington, DC

Alexander RM (1992) The human machine. Columbia University Press, New York

Azevedo F (2000) Designing representations of terrain: a study in meta-representational competence. J Math Behav 19(4):443–480

Azevedo FS, diSessa AA, Sherin BL (2012) An evolving framework for describing student engagement in classroom activities. J Math Behav 31(2):270–289. doi:10.1016/j.jmathb.2011.12.003

Ballarotti MG, Saba MMF, Pinto O (2005) High-speed camera observations of negative ground flashes on a millisecond-scale. Geophys Res Lett 32(23):L23802. doi:10.1029/2005gl023889

Barbosa TM, Bragada JA, Reis VCM, Marinho DA, Carvalho C, Silva ANJ (2010) Energetics and biomechanics as determining factors of swimming performance: updating the state of the art. J Sci Med Sport 13(2):262–269. doi:10.1016/j.jsams.2009.01.003

Barr R, Pandy M, Petrosino A, Svihla V (2005) Challenge-based instruction: the VaNTH biomechanics learning modules. Paper presented at the Frontiers in Education, 2005. FIE '05. Proceedings 35th annual conference

Barsalou LW (1999) Perceptual symbol systems. Behav Brain Sci 22(04):577–660

Bell P, Lewenstein B, Shouse AW, Feder MA (2009) Learning science in informal environments: people, places, and pursuits. National Academies Press, Washington, DC

Boyd A, Rubin A (1996) Interactive video: a bridge between motion and math. Int J Comput Math Learn 1(1):57–93

Brown AL (1992) Design experiments: theoretical and methodological challenges in creating complex interventions in classroom settings. J Learn Sci 2(2):141–178

Danish JA, Enyedy N (2006) Negotiated representational mediators: how young children decide what to include in their science representations. Sci Educ 91(1):1–35

diSessa AA (2002) Students' criteria for representational adequacy. In: Gravemeijer K, Lehrer R, Verschaffel L (eds) Symbolizing, modeling and tool use in mathematics education. Springer, New York, pp 105–130

diSessa AA (2004) Metarepresentation: native competence and targets for instruction. Cogn Instr 22(3):293–331

diSessa AA, Hammer D, Sherin B, Kolpakowski T (1991) Inventing graphing: meta-representational expertise in children. J Math Behav 10:117–160

Duschl RA, Schweingruber HA, Shouse AW (2007) Taking science to school: learning and teaching science in grades K-8. The National Academies Press, Washington, DC

Elby A (2000) What students' learning of representations tells us about constructivism. J Math Behav 19:481–502

Enyedy N (2005) Inventing mapping: creating cultural forms to solve collective problems. Cogn Instr 23(4):427–466

Enyedy N, Danish J, Delacruz G, Kumar M (2012) Learning physics through play in an augmented reality environment. Int J Comput Support Collab Learn 7(3):347–378. doi:10.1007/s11412-012-9150-3

Gravel BE (2009) Science of SAM: why animation is good for the classroom. Unpublished white paper. Tufts University, Medford, MA

Hall R, Nemirovsky R (2011) Introduction to the special issue: modalities of body engagement in mathematical activity and learning. J Learn Sci 21(2):207–215. doi:10.1080/10508406.2011.611447

Karmiloff-Smith A (1990) Constraints on representational change: evidence from children's drawings. Cognition 34:57–83

Klein SS, Sherwood RD (2005) Biomedical engineering and cognitive science as the basis for secondary science curriculum development: a three year study. School Sci Math 105(8):384–401. doi:10.1111/j.1949-8594.2005.tb18059.x

Koleza E, Pappas J (2008) The effect of motion analysis activities in a video-based laboratory in students' understanding of position, velocity and frames of reference. Int J Math Educ Sci Technol 39(6):701–723

Lee VR (2013) The Quantified Self (QS) movement and some emerging opportunities for the educational technology field. Educ Technol 53(6):39–42

Lee VR, Drake J (2013a) Digital physical activity data collection and use by endurance runners and distance cyclists. Technol Knowl Learn 18(1–2):39–63. doi:10.1007/s10758-013-9203-3

Lee VR, Drake J (2013b) Quantified recess: design of an activity for elementary students involving analyses of their own movement data. In: Hourcade JP, Miller EA, Egeland A (eds) Proceedings of the 12th international conference on interaction design and children 2013. ACM, New York, NY, pp 273–276

Lee VR, DuMont M (2010) An exploration into how physical activity data-recording devices could be used in computer-supported data investigations. Int J Comput Math Learn 15(3):167–189. doi:10.1007/s10758-010-9172-8

Lee VR, Thomas JM (2011) Integrating physical activity data technologies into elementary school classrooms. Educ Tech Res Dev 59(6):865–884. doi:10.1007/s11423-011-9210-9

Lehrer R, Romberg TA (1996) Exploring children's data modeling. Cognition & Instruction 14(1):69–108

Lieberman DE, Venkadesan M, Werbel WA, Daoud AI, Andrea S, Davis IS, Pitsiladis Y (2010) Foot strike patterns and collision forces in habitually barefoot versus shod runners. Nature 463(7280):531–535. doi:10.1038/nature08723

Louca LT, Zacharia ZC (2011) Modeling-based learning in science education: cognitive, metacognitive, social, material and epistemological contributions. Educ Rev 64(4):471–492. doi:10.1080/00131911.2011.628748

McDougall C (2009) Born to run: a hidden tribe, superathletes, and the greatest race the world has never seen. Alfred A. Knopf, New York

McGinnis P (2013) Biomechanics of sport and exercise. Human Kinetics, Champaign, IL

Moher T, Ching CC, Schaefer S, Lee VR, Enyedy N, Danish J, Rubin A (2014) Becoming reflective: designing for reflection on physical performances. In: Polman JL, Kyza EA, O'Neill DK, Tabak I, Penuel WR, Jurow AS, O'Connor K, Lee T, D'Amico L (eds) Learning and becoming in practice: the international conference of the learning sciences (ICLS) 2014, vol 3. ISLS, Boulder, CO, pp 1273–1282

National Research Council (1999) How people learn: brain, mind, experience, and school. National Academy Press, Washington, DC

Pandy MG, Petrosino AJ, Austin BA, Barr RE (2004) Assessing adaptive expertise in undergraduate biomechanics. J Eng Educ 93(3):211–222. doi:10.1002/j.2168-9830.2004.tb00808.x

Papert S (1980) Mindstorms: children, computers, and powerful ideas. Basic Books, New York, NY

Papert S (1991) Situating constructionism. Ablex Publishing, Norwood, NJ

Parnafes O (2007) What does "Fast" Mean? Understanding the physical world through computational representations. J Learn Sci 16(3):415–450

Penner DE, Giles ND, Lehrer R, Schauble L (1997) Building functional models: designing an elbow. J Res Sci Teach 34(2):125–143

Penner DE, Lehrer R, Schauble L (1998) From physical models to biomechanics: a design-based modeling approach. J Learn Sci 7(3–4):429–449

Piaget J (1929) The child's conception of the world. Brace & Company, Inc., Harcourt

Reis PM, Jung S, Aristoff JM, Stocker R (2010) How cats lap: water uptake by Felis catus. Science 330(6008):1231–1234. doi:10.1126/science.1195421

Richland LE, Zur O, Holyoak K (2007) Cognitive supports for Analogies in the mathematics classroom. Science 316:1128–1129

Roselli RJ, Brophy SP (2003) Redesigning a biomechanics course using challenge-based instruction. Eng Med Biol Mag IEEE 22(4):66–70. doi:10.1109/memb.2003.1237504

Schwartz D, Lin X, Brophy S, Bransford JD (1999) Toward the development of flexibly adaptive instructional designs. In: Reigeluth CM (ed) Instructional-design theories and models, vol 2. Lawrence Erlbaum, Mahwah, NJ, pp 183–214

Schwarz CV, Reiser BJ, Davis EA, Kenyon L, Achér A, Fortus D, Krajcik J (2009) Developing a learning progression for scientific modeling: making scientific modeling accessible and meaningful for learners. J Res Sci Teach 46(6):632–654

Searl E, Gravel BE, Rogers C (2009) SAM animation (version 1.1). Tufts University, Medford, MA

Sherin B (2000) How students invent representations of motion: a genetic account. J Math Behav 19(4):399–441

Steinkuehler C, Duncan S (2008) Scientific habits of mind in virtual worlds. J Sci Educ Technol 17(6):530–543. doi:10.1007/s10956-008-9120-8

Thoroddsen ST, Etoh TG, Takehara K (2008) High-speed imaging of drops and bubbles. Annu Rev Fluid Mech 40(1):257–285. doi:10.1146/annurev.fluid.40.111406.102215

Verschaffel L, Reybrouck M, Jans C, Van Dooren W (2010) Children's criteria for representational adequacy in the perception of simple sonic stimuli. Cogn Instruct 28(4):475–502

Wilkerson-Jerde MH, Gravel BE, Macrander CA (2014) Exploring shifts in middle school learners' modeling activity while generating drawings, animations, and computational simulations of molecular diffusion. J Sci Educ Technol. doi:10.1007/s10956-014-9497-5

Windschitl M, Thompson J, Braaten M (2008) Beyond the scientific method: model-based inquiry as a new paradigm of preference for school science investigations. Sci Educ 92(5):941–967

Yuan M, Kim NJ, Drake J, Smith S, Lee VR (2014) Examining how students make sense of slow-motion video. In: Polman JL, Kyza EA, O'Neill DK, Tabak I, Penuel WR, Jurow AS, O'Connor K, Lee T, D'Amico L (eds), Learning and becoming in practice: the international conference of the learning sciences (ICLS) 2014, vol 3. ISLS, Boulder, CO, pp 1617–1618