A kinesthetic circulatory system model for teaching fluid dynamics

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Abstract: Students often leave Introductory Physics for Life Science (ILPS) courses without a solid understanding of fluid dynamics, which is necessary for them to be successful in their future biology courses. In an effort to reconcile this issue, researchers at UNE have focused on improving students' understanding of the circulatory system. This requires students to apply multiple fluid dynamics concepts, specifically, conservation of mass and the Bernoulli and Hagen-Poiseuille Principles. The researchers developed a kinesthetic circulatory system model made of transparent plastic tubing of different radii and branched connectors. This hands-on model enabled students to see the fluid travel at different speeds (visually) and different pressures (using digital pressure sensors) similar to the cardiovascular system. Preliminary evaluation data from close-ended multiple-choice assessments and open-ended assessments indicates significant improvement in student understanding of conservation of mass and Bernoulli's principle but little improvement of Hagen-Poiseuille's Principle.

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I. INTRODUCTION

The University of New England Physics Education Research Group (UNEPERG) has been incorporating active learning strategies [1-3] in its introductory physics sequence for the past 15 years. Despite a systematic effort to reorganize the sequence in order to better articulate course objectives and to help students conceptualize basic physics principles, there has been a steady decline in overall research-based assessment gains [4]. This was attributed to a lack of student ownership in a learning process that appeared (to the students) not to provide marketable skills and a lack of tangible conceptual representation. In an effort to reform the physics content in a presentation consistent with guided inquiry, UNEPERG concentrated on the contextually highly relevant but conceptually difficult area of fluid dynamics. UNEPERG has developed and begun to assess a kinesthetic circulatory system model (KCSM) that remains true to the principles of guided inquiry while providing students with relevant content and approaching from multiple learning styles [5].

A. Instructional Innovation

The KCSM developed by our research integrates an authentic biological example into fluid physics instruction in order to improve our Introductory Physics for the Life Sciences (IPLS) physics sequence [6]. There were two major motivations behind this project; the first was to provide conceptual physics representation relevant to life science majors' career needs and the second was to address the difficulties that students harbored surrounding three fluid dynamics concepts: conservation of mass, the Bernoulli Principle (BP), and the Hagen-Poiseuille Principle (HPP). We observed during previous investigations of student misunderstanding of BP [7] that a holistic approach might help compartmentalize the confusing relationships between flow rate, speed, pressure and other fluid properties. The objective was to help reconcile apparent fluid dynamics paradoxes in order to improve student organization and understanding of these concepts. The basic fluid physics principles described below are traditionally treated separately (or, sometimes, not at all). Students often see no relationship between these concepts and reality. Preliminary assessment tools were developed to help analyze the effectiveness of the instruction.

B. Basic Fluid Physics

The KCSM includes three basic fluid physics concepts: conservation of mass (Eq. 1), BP (Eq. 2), and HPP (Eq. 3).

$$Q = \frac{\Delta V}{\Delta t} = A_{\text{in}} v_{\text{in}} = A_{\text{out}} v_{\text{out}} \qquad (1)$$

$$\Delta P = \rho g \Delta y - \frac{1}{2}\rho \Delta\left(v^2\right) \qquad (2)$$

$$\Delta P = \frac{8\eta \text{LQ}}{\pi r^4} \qquad (3)$$

In Eq. 1, the flow rate "Q" (volume per unit time) of a fluid through a closed system depends on variable cross-sectional areas "A" and fluid speeds "v." In Eq. 2, the pressure difference "ΔP" of fluid density "ρ" is due to gravitational field "g," depth of the fluid in the column "Δy," and local fluid speed "v." Eq. 3 characterizes the global pressure difference that depends on the fluid's viscosity "η," length "L," flow rate, and tube radii "r" in a closed system.

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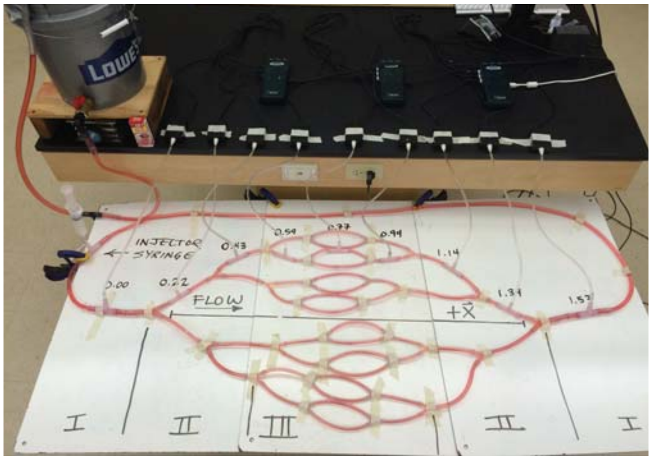

FIG 1. Model circulatory system consisting of transparent tubing, liquid reservoir, pressure sensors, and bubble injector. Scale: +x axis is 1.00 m in length.

II. INSTRUCTIONAL DESIGN

A. Kinesthetic Model

The hands-on KCSM (Fig. 1) consists of transparent plastic tubing expanding from one large inflow tube at left into 16 smaller tubes and contracting back into a single larger tube on the right. Nine ports measure the pressure of flowing fluid (red-dyed water) at approximately equal lengths across the system. Flow was hydrostatically driven by a 5-gallon reservoir approximately 50 cm above the tubing (top left) at a rate of about 50 mL/s, and the speed of the fluid was calculated by monitoring air bubbles trapped in the moving fluid. The clear vinyl tubing had inner tube diameters of 3/8" (region I), 5/16" (region II), and ¼" (region III). 3/8" inner diameter branched "Y" adapters were used in the transition from regions I to II, 5/16" from region II to III and ¼" in region III.

B. Quantitative Analysis

Small air bubbles were intentionally injected into the system through a syringe (Fig. 1) and the flowing bubbles were video-recorded using high speed (120 fps) smart phone cameras. The fluid speeds were then calculated through video analysis. Nine internal fluid pressures can be measured simultaneously with three Vernier LabPros, each with three pressure sensors, and plotted versus location along the paths (Fig. 1). The results (Fig. 2) approximate the general shape of blood pressure speeds found in the human circulatory system (ignoring arterial elasticity) [8].

C. Instruction & Demonstration

The concepts behind conservation of mass and BP were first introduced to students separately through traditional demonstrations [4,9] followed by quantitative exercises. In the subsequent class, after review of these concepts, the

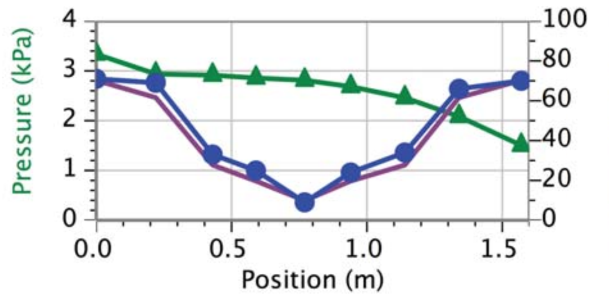

FIG 2. Left axis (triangle) are experimental pressure measurements as a function of location of sensors shown in Fig. 1. Right axis represents experimental fluids speed (circles) that are in good agreement with predicted fluid speeds (solid line) based on conservation of mass.

KCSM was shown to the students. Before observing liquid flowing through the model, students were asked to make a graphical prediction based on the question, "how does speed depend on position?". The students worked in groups of two or three and drew up their white board predictions after ten minutes of discussion (Fig. 3), based on their understanding of the fluids concepts developed in the previous classes. Students then presented their whiteboards for the entire class to view and discuss.

After discussion, the students surrounded the model and watched the flow of liquid through it. By watching the air bubbles, the students easily saw faster fluid motion in region I and slower motion in region III, as predicted by continuity. Next, the students were again asked to address the question, "how does pressure depend on position?". Again, students graphed their predictions, followed by discussion and observation of the actual pressure of the flowing liquid in the system. Students made consistent predictions based on BP, but did not match Fig. 2 because their fluid models were incomplete. HPP was introduced at that juncture, with the emphasis being placed on the impact of fluid viscosity, length, and radius of KCSM tubing.

(a)

(b)

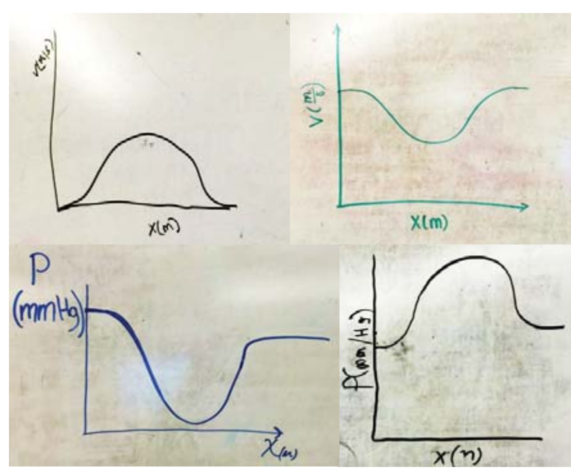

FIG 3. Student predictions: (a) Common graphical representations of speed vs. position (~50% correct). (b) Common graphical representations of pressure vs. position (consistent but incorrect).

III. RESEARCH DESIGN

A. Participants

210 introductory Physics students at UNE participated in this study. 95% were life science majors with this being the only physics course they would take; the majority of students concurrently took anatomy and physiology (A&P). The students were divided into three groups according to instructors. The purpose of groups 1 (N=137) and 2 (N=57) was to preliminarily test the effectiveness of the model before A&P instruction (group 1) or during (group 2). Group 3 (N=16) provided open-ended responses that would help determine misconceptions and reliability of the assessment tool.

B. Assessment Questions & Test Administration

The instructional design described previously was preceded and followed by identical assessments for the first two groups and a similar open-ended assessment for group 3. The KCSM covered the fluid dynamics concepts without teaching to these assessments. Group 1 was pre- and post-tested with a second-generation, 12-question survey, largely developed in-house based on common student errors observed by instructors [10]. The purpose of the assessments was to test students' conceptual understanding of physics fluid concepts described in section I.B. Five of these questions were selected for analysis based on their relevance to the concepts demonstrated by the KCSM. The questions included multiple representations of similar concepts including a verbal question on continuity (Q1), a diagrammatic question on continuity and BP (Q2), a diagrammatic question on HPP (Q3), a graphical question on continuity and BP (Q4), and a graphical question on continuity and HPP (Q5). The same test was administered one to two weeks after completion of the fluids content.

Group 2 was given the same pre-test during the second semester of the introductory physics course. The pre-test was administered after a brief introduction to fluid dynamics (one lecture), which somewhat clouds the analysis of the results. The intention was to have the physics instruction coincide with the coverage of the circulatory system in the A&P course. The goal was to see if previewing the content from the biology perspective changed the student assessment outcomes.

Group 3 consisted of students in an accelerated summer course and was subject to an open-ended assessment based on the same multiple-choice questions given to the other two groups. This was administered shortly after the KCSM was introduced and analyzed by students. The purpose of this activity was to determine the reliability of the multiple-choice assessment as well as gain a better understanding of any misconceptions students harbored after the instructional design was complete.

IV. RESULTS AND DISCUSSION

A. Assessment

1. Close-ended Pre- and Post-test Results

Fig. 4 shows the normalized gain (Gain) [11] results from the five relevant fluid dynamics questions from our multiple-choice assessment, available online [10]. The average score on the pre-tests from group 1 was 19.5%, which is approximately equivalent to random guessing. The average score on the pre-tests from group 2 was 33.7%, significantly higher than random guessing according to an unpaired, two-tailed t test [$t(56) = 7.899$, $\alpha = 0.05$]. These results appear to be consistent with the fact that group 2 had already been introduced to the topic of continuity before the pre-test and that the majority of students were learning about the circulatory system in parallel in A&P.

To provide a frame of reference for these preliminary results we compared them to normalized gains from a modified version of an earlier generation conceptual fluids dynamics assessment we used previously based on an instrument developed for engineers [12]. Even in our reformed physics laboratory setting the typical normalized gains for our students was only around 23%. In contrast, using *similar* questions, the average (Avg.) Gain was 45.9% for group 1 students and 42.9% for group 2 students. The results are similar and suggest that teaching the content exclusively in physics or in parallel with A&P made no difference, a somewhat unexpected result. An encouraging observation was that there did not appear to be any instructor bias since the groups were taught by a total of four different lecturers.

In summary the students had improved normalized gains in fluid dynamics compared to our introductory physics students from previous years. Even though groups 1 and 2 had different starting points they appeared to achieve the same approximate gains after exposure to the KCSM.

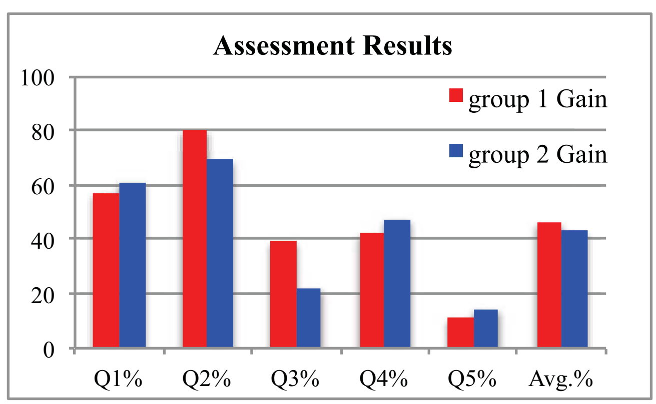

FIG 4. Comparison of group 1 and 2 normalized gains by question based on specific assessment questions covered by the KCSM.

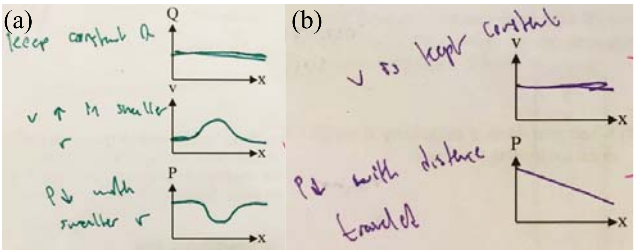

FIG 5. (a) Correct depiction of flow rate, speed, and pressure of ideal fluid through a restriction. (b) Incorrect depiction of speed and partially correct depiction of pressure of a real fluid through a restriction. (Both depictions were made by the same student.)

2. Open-ended Post-test Results

The purpose of group 3 students was to help refine the preliminary assessment through open-ended responses. Small instructional deviations were made to include the idea of fluid resistance before introducing the KCSM. The students were then guided to make in-class predictions of the fluid speed and pressure versus position using the KCSM. The requested predictions were similar in concept to Q4 and Q5 of the multiple-choice assessment. Even with the introduction to fluid resistance, the group 3 students still made graphical predictions assuming ideal fluid behavior, meaning students made little to no connection between fluid resistance and pressure.

Group 3 students made similar whiteboard predictions regarding speed and pressure versus position as those of groups 1 & 2 (Fig. 3). About 50% of students accurately predicted the speed versus position profile. The common mistake in inaccurate fluid speed predictions based on continuity was neglecting the combined cross-sectional area of the capillaries compared to the aorta which was confirmed by demonstration of the KCSM. Again, the group 3 students made consistent, but still inaccurate, predictions of pressure based on BP response to fluid speed. The importance of fluid resistance was then demonstrated through observation of real-time pressure data (Fig. 2).

The post-test for group 3 involved a written assessment that included open-ended versions of the five multiple-choice questions analyzed for groups 1 & 2. Overall trends for all three groups were the same. That is, the KCSM appeared to be very successful in clarifying the concepts of conservation of mass and BP (Fig. 4: Q1,2,4 equivalent to Fig. 5a). However, the understanding of the difference between ideal and viscous fluids was less successful (Fig. 4: Q3,5 equivalent to Fig 5b).

V. CONCLUSIONS

The improvements in understanding the effect of viscosity with respect to HPP (Gains on Q3,5) were small. This is problematic because fluid resistance plays the dominant role in pressure drop across the circulatory system. The assessment results suggests the need for a modification in the instructional design, such as an experiment that demonstrates the variables described in Eq. 3, to improve students' conceptual understanding of HPP.

Curiously, the similarity of assessment results between the two groups suggests that it makes no difference if the KCSM is taught alone in physics or in parallel with A&P courses. In the future we plan to use an attitude survey to compare how the students feel about the content either looking at it solely in physics or in parallel with anatomy and physiology.

Our preliminary assessment results indicate that the KCSM helps students to develop a more holistic understanding of both important physics fluid principles, as well as the physiology of the circulatory system. The enhanced understanding can also be applied to other systems of the human body, such as the respiratory system, allowing students to use their physics knowledge in other units of their A&P courses. This is consistent with the recommendations that all biology students have a comprehensive knowledge base of fluid dynamics principles [11]. Future efforts will also include improving the preliminary assessment by incorporating student generated open-ended distractors into the conceptual fluid dynamics survey and to compare the model efficacy by deploying the assessment in more traditional physics lecture-lab environments without the use of the KCSM.

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