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Computer Simulation and Animation (CSA) for Learning Particle Dynamics: Force and Acceleration in Curvilinear Motion*

NING FANG** and YONGQING GUO
Department of Engineering Education, College of Engineering, Utah State University, 4160 Old Main Hill, Logan, UT 84322, USA.
E-mail: ning.fang@usu.edu

Force and acceleration are two fundamental concepts in engineering dynamics, a second-year foundational course required in many undergraduate engineering programs. Research has shown that many students do not possess solid conceptual understanding and problem-solving skills when dealing with force and acceleration. In the present study, two new computer simulation and animation (CSA) learning modules are developed to enhance student learning of force and acceleration in curvilinear motion in particle dynamics, an essential part of engineering dynamics. Quantitative research has been conducted, involving a total of 286 engineering undergraduates in the comparison and intervention groups. Non-parametric statistical analysis of the collected data was conducted. The results show that the two CSA learning modules developed in the present study have a statistically significant effect on student learning. Student participants in the intervention group achieved 40%–44% average normalized learning gain; whilst those in the comparison group achieved only 4%–15% average normalized learning gain.

Keywords: computer simulation and animation (CSA); particle dynamics; force; acceleration; curvilinear motion

1. Introduction

1.1 Engineering Dynamics and Student Learning Challenges

Engineering dynamics focuses on the studies of force, motion, and interactions between force and motion. Built upon Newtonian mechanics, engineering dynamics is a second-year foundational course required in undergraduate engineering programs, such as mechanical, aerospace, civil, and environmental engineering [1–3]. Student learning in this critical course has a significant impact on student performance in subsequent third-year and fourth-year courses, for instance, fluid dynamics, advanced dynamics, vibration, and machine design.

Student learning in engineering dynamics, however, has been a great challenge for many undergraduates due to the numerous concepts and problem-solving procedures this course covers [4, 5]. In most cases, dynamics concepts are highly abstract and require students to have strong spatial thinking and reasoning skills. The procedures involved in problem solving also require students to have solid mathematical skills because conceptual understanding alone is insufficient for effective problem solving in engineering dynamics [1–3].

Take force and acceleration, two fundamental concepts in engineering dynamics and physics mechanics, as examples. Recent studies have shown that students have numerous misconceptions about force and acceleration [6–9]. It is not uncommon for students to analyze and solve dynamics problems based on statics viewpoints. In statics problems, external forces that an object is subjected to are in equilibrium. The summation of all external forces equals zero. In dynamics problems, however, external forces that an object is subjected to are not in equilibrium. The summation of all external forces no longer equals zero; but is related to the object's mass and acceleration (i.e., Newton's second law of motion).

Student misconceptions about force and acceleration are especially evident when dealing with curvilinear motion [10–13]. It is not uncommon for students to analyze and solve curvilinear motion problems based on rectilinear motion viewpoints. In linear motion, force and acceleration do not have any components. In curvilinear motion, force and acceleration each have two or three components, depending on whether the motion occurs in a two-dimensional plane or a three-dimensional space. The magnitude and direction of each force and acceleration component can vary as the object moves.

1.2 Computer Simulation and Animation

A variety of engineering pedagogies have been developed or adopted to enhance student learning in engineering dynamics, for example, active learning via physical models [14], videos [15], and games

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** Corresponding author.

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[16]; problem-based learning [17]; project-based learning [18]; blended and collaborative learning [19], and flipped classroom [20, 21]. Either computer simulation or computer animation has been integrated into some (not all) of these engineering pedagogies [22–25].

Although used interchangeably by many in the literature, computer simulation and computer animation are two different terms in terms of their focuses. Computer simulation focuses on helping students understand how to solve the technical problem that they are studying. Most often, computer simulation also provides numerical answers to technical problems. Computer animation, as its name implies, focuses on showing students on a computer screen how an object moves in a two-dimensional plane or three-dimensional space. Computer animation is particularly helpful for those students who do not have strong abilities or skills in spatial thinking and reasoning.

The vast majority of computer software programs developed for engineering dynamics is computer animation. Stanley [26] developed computer animation programs to illustrate a projectile motion. Flori, Koen and Oglesby [27] developed computer programs for animating various types of motions involved in engineering dynamics. The well-known computer software PhET Interactive Simulations [28] contains simulations in physics mechanics, a subject closely related to engineering dynamics. Some simulations in PhET (Physics Education Technology) focus on the demonstration of various types of motions [28]; therefore, they might be more accurately called computer animations than computer simulations. The terminology difference between computer simulation and computer animation has been explained in the previous paragraph of this paper. Table 1 summarizes the three computer software programs described above.

1.3 The Innovation and Contribution of the Present Study

The present study is innovative in terms of both development and research work involved. First, two new learning modules are developed to enhance student learning of force and acceleration in curvilinear motion in particle dynamics. Engineering dynamics consists of two parts: particle dynamics and rigid-body dynamics. Particle dynamics plays a significant role in engineering dynamics as it lays an essential foundation for students to learn subsequent topics in rigid-body dynamics.

In the two learning modules developed in the present study, computer simulation is integrated into computer animation. This integration not only helps students develop conceptual understanding but also problem solving in particle dynamics. Therefore, these two modules are called computer simulation and animation (CSA) learning modules.

Second, quantitative research involving students in the comparison and intervention groups was conducted in the present study to assess the effectiveness of the CSA learning modules. Existing research on the effectiveness of computer software developed for engineering dynamics [26, 27] has been heavily depending on questionnaire surveys and interviews with students in a single group. Questionnaire surveys and interviews are highly valuable as they provide insights into student perspectives about computer simulation and animation. However, questionnaire surveys and interviews are subjective opinions in their nature and cannot measure the extent to which students have *actually learned* from computer simulation and/or computer animation. The present study bridges this important research gap.

In the remaining sections of this paper, the development of two CSA learning modules is described first, including the design of technical problems and the important features of these learning modules. Then, research and data collection methods are introduced, followed by the presentation and analysis of the research results. The limitations of the present study are described. Conclusions are made at the end of the paper.

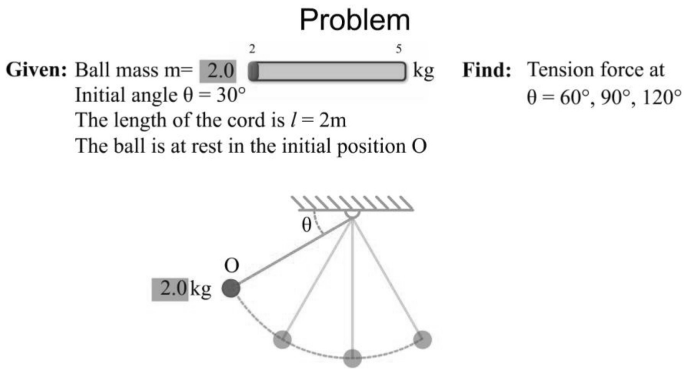
2. Development of Two CSA Learning Modules

2.1 Design of Technical Problems

To enhance student learning of force and acceleration in curvilinear motion in particle dynamics, two CSA learning modules are developed. Learning module I was developed for normal and tangential coordinates, and learning module II for polar coordinates. Force and acceleration are resolved into different components based on the coordinate

Table 1. Representative computer software programs that involve curvilinear motion in engineering dynamics and physics mechanics

Type of computer software programs	Literature resources	Program focuses
Computer animations	Stanley [26]	Interactive web-based animations for particle kinematics
Computer simulations	Flori, Koen and Oglesby [27]	Problem simulations for particle and rigid-body dynamics
Computer animations	PhET Interactive Simulations [28]	Interactive animations for physics



Problem

Given: Ball mass m= 2.0 kg

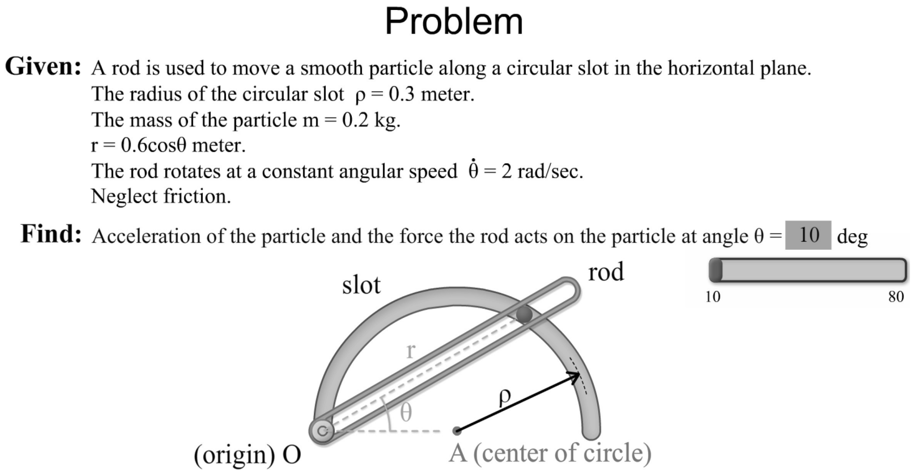
Initial angle θ = 30°

The length of the cord is *l* = 2m

The ball is at rest in the initial position O

Find: Tension force at θ = 60°, 90°, 120°

Fig. 1. The technical problem for CSA learning module I.



Problem

Given: A rod is used to move a smooth particle along a circular slot in the horizontal plane.

The radius of the circular slot ρ = 0.3 meter.

The mass of the particle m = 0.2 kg.

r = 0.6cosθ meter.

The rod rotates at a constant angular speed $\dot{\theta}$ = 2 rad/sec.

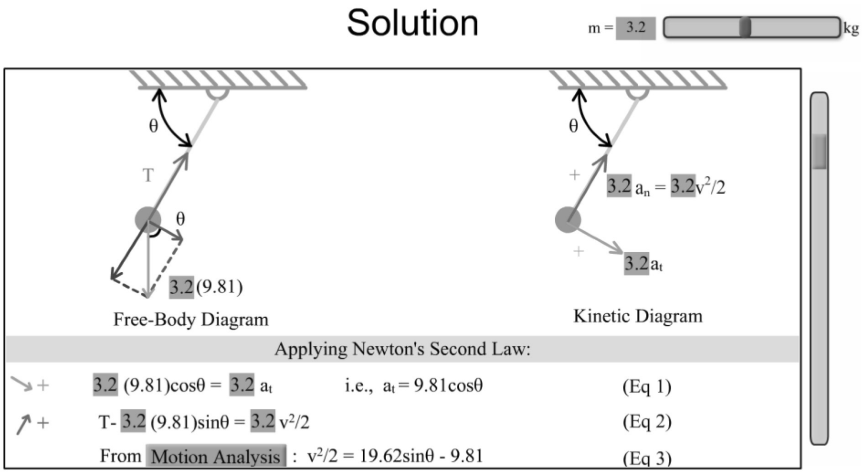
Neglect friction.

Find: Acceleration of the particle and the force the rod acts on the particle at angle θ = 10 deg

Fig. 2. The technical problem for CSA learning module II.

systems employed. The learning objective is to apply Newton's second law of motion to determine the force acting on a particle and the acceleration of the particle in curvilinear motion based on normal and tangential coordinates (for learning module I) and polar coordinates (for learning module II).

Two technical problems were designed for learning modules I and II as shown in Figs. 1 and 2, respectively. In Fig. 1, a ball is linked to the end of a cord and rotates from its initial position on the left side to the position on the right side. Tension force changes as the ball changes its position. In Fig. 2, a rod drives a smooth particle along a circular slot in the horizontal plane. The acceleration of the particle and the force the rod acts on the particle change as the rod changes its position.



Solution

m = 3.2 kg

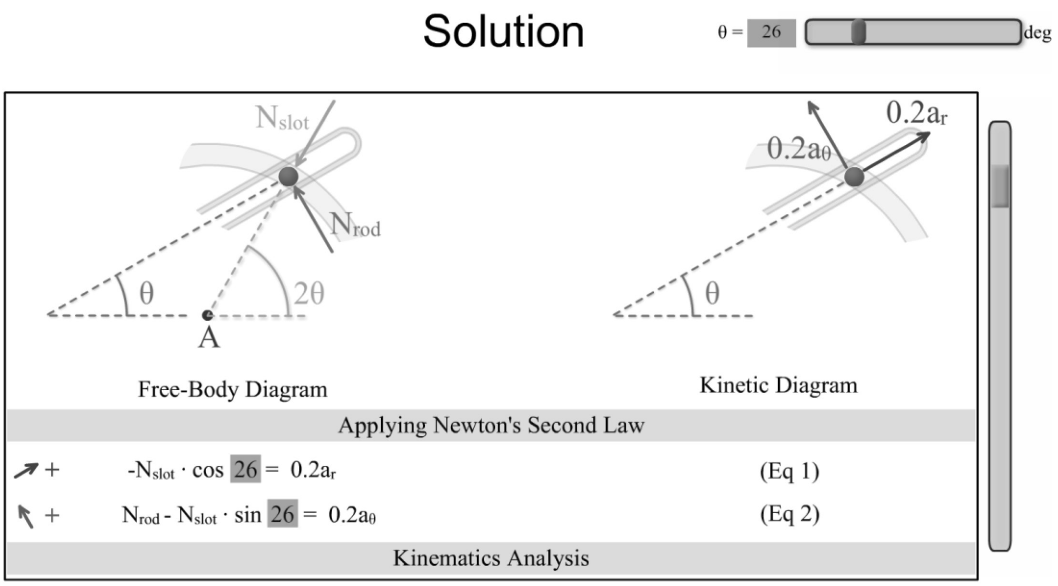
Applying Newton's Second Law:

↘+ 3.2 (9.81)cosθ = 3.2 a_t i.e., a_t = 9.81cosθ (Eq 1)

↗+ T- 3.2 (9.81)sinθ = 3.2 $v^2/2$ (Eq 2)

From Motion Analysis : $v^2/2$ = 19.62sinθ - 9.81 (Eq 3)

Fig. 3. The interactive computer GUI for CSA learning module I.



↗ + $-N_{slot} \cdot \cos 26 = 0.2a_r$ (Eq 1)

↖ + $N_{rod} - N_{slot} \cdot \sin 26 = 0.2a_\theta$ (Eq 2)

Fig. 4. The interactive computer GUI for CSA learning module II.

2.2 *Features of the CSA Learning Modules*

Adobe Flash was employed to develop computer codes for the two CSA learning modules with the following two important features. First, both learning modules allow students to observe the motion of the particles involved. In other words, both learning modules have a built-in animation function. This animation function is particularly helpful for those students who have not yet possessed strong skills in spatial thinking and reasoning.

Second, both learning modules incorporate step-by-step problem-solving procedures and allow students to vary inputs to see how outputs simultaneously change. Figures 3 and 4 show interactive computer graphical user interfaces (GUIs) for learning module I and II, respectively. In Fig. 3, students can change the value of mass (m) to see how tension force varies. In Fig. 4, students can change the position of the rod (θ) to see how force and acceleration change. In other words, both learning modules have a built-in simulation function. This simulation function is helpful for students to develop not only conceptual understanding but also problem-solving skills when applying Newton's second law in curvilinear motion.

3. Research Method and Data Collection

3.1 *Research Method*

The present study has the following research questions: Did the CSA learning modules developed in the present study enhance student learning of force and acceleration in curvilinear motion in particle dynamics? If yes, to what extend did these learning modules improve student learning?

To answer these research questions, quantitative research method [29, 30] was employed including student participants in a comparison group and an intervention group. The comparison group did not use the CSA learning modules; whist the intervention group used the CSA learning modules. The same instructor (i.e., the first author of this paper) taught both groups with the same textbook and course syllabus. Therefore, the effect of instructors was eliminated.

3.2 *Data Collection*

A total of 286 student participants were recruited from an Engineering Dynamics course that the first author of this paper taught. So that educational research did not interfere with normal classroom teaching, student participants in the comparison group learned engineering dynamics from the instructor in Semester A, and student participants in the intervention group learned engineering dynamics from the same instructor in Semester B. The vast majority of student participants were from two engineering departments at the authors' institution. The following paragraphs list the number of student participants in each learning module:

CSA learning module I: 64 in the comparison group and 81 in the intervention group.
CSA learning module II: 62 in the comparison group and 79 in the intervention group.

Both groups of student participants took the same pre- and post-tests using the same assessment instrument. For each student participant, normalized learning gain [31] was calculated as [post-test score (%) – pre-test score (%)] divided by [100% –

Table 2. Normality test results for CSA learning module I

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
Category	**Statistic**	**df**	**Sig.**[b]	**Statistic**	**df**	**Sig.**[b]
Pre-test scores						
Comparison group	0.192	64	0.000	0.929	64	0.001
Intervention group	0.212	81	0.000	0.917	81	0.000
Post-test scores						
Comparison group	0.164	64	0.000	0.945	64	0.006
Intervention group	0.156	81	0.000	0.931	81	0.000
Normalized learning gains						
Comparison group	0.150	64	0.001	0.954	64	0.019
Intervention group	0.105	81	0.028	0.946	81	0.002

[a] Lilliefors significance correction.
[b] The significance level (p-value) of less than 0.05 indicates a non-normal distribution of data.

Table 3. Normality test results for CSA learning module II

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
Category	**Statistic**	**df**	**Sig.**[b]	**Statistic**	**df**	**Sig.**[b]
Pre-test scores						
Comparison group	0.263	62	0.000	0.834	62	0.000
Intervention group	0.192	79	0.000	0.897	79	0.000
Post-test scores						
Comparison group	0.172	62	0.000	0.928	62	0.001
Intervention group	0.148	79	0.000	0.890	79	0.000
Normalized learning gains						
Comparison group	0.165	62	0.001	0.941	62	0.005
Intervention group	0.125	79	0.004	0.912	79	0.000

[a] Lilliefors significance correction.
[b] The significance level (p-value) of less than 0.05 indicates a non-normal distribution of data.

pre-test score (%)]. The average normalized learning gain was then calculated for the comparison group and the intervention group.

4. Results and Analysis

4.1 Normality Test

A normality test was conducted to determine if the data collected (i.e., pre-test scores, post-test scores, and normalized learning gains) are in a normal distribution. If the data are in a normal distribution, they can be subsequently analyzed using parametric statistical analysis, such as t-test. Otherwise, non-parametric statistical analysis, for instance, Mann-Whitney U test, should be employed to analyze the data.

Tables 2 and 3 show normality test results for CSA learning modules I and II, respectively. The significance level (p-value) of less than 0.05 indicates a non-normal distribution of data. As can be seen from columns 4 and 7 in Tables 2 and 3, the significance level (p-value) is less than 0.05 for all

Table 4. Descriptive analysis for CSA learning module I

Category	**Mean**	**Median**	**Standard deviation**	**Interquartile range**	**Skewness**	**Kurtosis**
Pre-test scores						
Comparison group	0.33	0.29	0.19	0.29	0.55	0.50
Intervention group	0.34	0.29	0.17	0.14	–0.03	–0.55
Post-test scores						
Comparison group	0.44	0.43	0.26	0.29	0.45	–0.26
Intervention group	0.63	0.71	0.26	0.43	–0.29	–0.90
Normalized learning gains						
Comparison group	0.15	0.07	0.38	0.38	0.20	0.87
Intervention group	0.44	0.50	0.41	0.55	–0.51	–0.41

Table 5. Descriptive analysis for CSA learning module II

Category	Mean	Median	Standard deviation	Interquartile range	Skewness	Kurtosis
Pre-test scores						
Comparison group	0.25	0.25	0.15	0.16	1.40	2.88
Intervention group	0.24	0.25	0.16	0.25	0.95	1.81
Post-test scores						
Comparison group	0.30	0.25	0.18	0.25	0.56	–0.15
Intervention group	0.56	0.50	0.34	0.63	–0.04	–1.45
Normalized learning gains						
Comparison group	0.04	0.00	0.27	0.31	–0.82	2.81
Intervention group	0.40	0.40	0.50	0.88	–0.53	–0.04

the data collected. Therefore, non-parametric statistical analysis was conducted for all subsequent statistical analysis.

4.2 Descriptive Analysis

Tables 4 and 5 show the results of descriptive analysis for CSA learning modules I and II, respectively. Note that mean and standard deviation, which are typically involved in parametric statistical analysis, are also listed in these two tables. This is because mean and standard deviation are commonly used and widely understood in the educational research community.

CSA learning module I: As can be seen from Table 4, for pre-test scores, the values of mean, median, and standard deviation are the same or nearly the same between the comparison and intervention groups. This implies that the two groups are comparable in terms of their knowledge and skills on the learning topics addressed in the present study, i.e., force and acceleration in curvilinear motion. However, the post-test score and normalized learning gain for the intervention group are greater than those for the comparison group: 0.63 vs. 0.44 for the post-test score and 0.44 vs. 0.15 for the normalized learning gain. In other words, the intervention group achieved 44% normalized learning gain due to the use of CSA learning module I. In contrast, the comparison group achieved only 15% normalized learning gain. The effectiveness of CSA learning module I is validated.

CSA learning module II: As can be seen from Table 5, for pre-test scores, the values of mean, median, and standard deviation are also the same or nearly the same between the comparison and intervention groups. This also implies that the two groups are comparable in terms of their knowledge and skills on the learning topics addressed in the present study. However, the post-test score and normalized learning gain for the intervention group are greater than those for the comparison group: 0.56 vs. 0.30 for the post-test score and 0.40 vs. 0.04 for the normalized learning gain. In other words, the intervention group achieved 40% normalized learning gain due to the use of CSA learning module II. In contrast, the comparison group achieved only 4% normalized learning gain. The effectiveness of CSA learning module II is also validated.

4.3 Mann-Whitney U Test

Mann-Whitney U test was conducted to determine if the difference in pre-test scores, post-test scores, and normalized learning gains between the comparison and intervention groups is statistically significant. The results are shown in Table 6.

Table 6. Mann-Whitney U test results

Category	Mann-Whitney U	Standardized test statistic (Z value)	Asymptotic sig. (2-sided test)
CSA learning module I			
Pre-test scores	2,690.0	0.404	0.686
Post-test scores	3,614.0	4.114	0.000*
Normalized learning gains	3,675.5	4.333	0.000*
CSA learning module II			
Pre-test scores	2,359.0	–0.389	0.697
Post-test scores	3,488.0	4.366	0.000*
Normalized learning gains	3,593.0	4.780	0.000*

* The asymptotic significance level (p-value) of less than 0.05 indicates a significant difference between the comparison and intervention groups.

In Table 6, the asymptotic significance level (p-value) of less than 0.05 indicates a significant difference between the comparison and intervention groups. As can be seen from column 4 in Table 6, the asymptotic significance level is greater than 0.05 for pre-test scores and less than 0.05 for post-test scores and normalized learning gains for both learning modules. In other words, the two learning modules developed from the present study have a statistically significant effect on student learning of force and acceleration in curvilinear motion.

The effect size of the two learning modules was further calculated as Z-value divided by sqrt(total sample size) [32]. The results show that the effect size is 0.36 for learning module I and 0.40 for learning module II. The values of 0.36 and 0.40 represent a medium effect size.

5. Discussions and Limitations of the Present Study

The results described in the above section demonstrate the effectiveness of computer simulation and animation in improving student learning of force and acceleration in curvilinear motion in particle dynamics. Two efforts contribute to the success of CSA. First, computer simulation is integrated into computer animation, so not only can students visualize the motion of particles, but they can also master step-by-step problem-solving procedures. Research [4, 5] has shown that both spatial visualization and procedural skills are critical for effective problem solving in engineering dynamics.

Second, the technical problems addressed in computer simulation and animation are carefully designed. The CSA learning modules described in this paper include two technical problems. These problems might be easy for experienced instructors. However, these problems might still be challenging for students as they are novices. The students in the comparison group, who did not use CSA, achieved an average normalized learning gain of only 15% for CSA learning module I and only 4% for CSA learning module II. In future work, more CSA learning modules with various levels of difficulty will be developed to meet the needs of diverse students.

It also needs to be noted that CSA learning modules should not be employed to replace regular teaching. Instead, they should be used as a supplement tool to assist teaching and learning both inside and outside the classroom. For instance, when an instructor teaches relevant course materials in the classroom, the instructor can demonstrate CSA to students in the class. The animation function of CSA would help students develop a conceptual understanding of the problem. The simulation function of CSA would help students understand how dynamics concepts and principles are used for effective problem-solving.

The present study has two primary limitations. First, all 286 student participants were recruited from the authors' institution, a public research institution in the Mountain West region of the United States. Approximately 85% of student participants were males and only 15% were females. The vast majority of them were white students. As such, they cannot represent a diverse student body across the country, especially those students traditionally underrepresented in engineering, such as Hispanic and African American students. Efforts will be made in the future study to recruit diverse student participants from other institutions.

Second, in its essence, the present study is a quasi-experimental study rather than an experimental study where student participants are randomly selected [29]. The students in the comparison and intervention groups were recruited from two semesters, respectively, from an engineering dynamics course they were taking. The purpose of doing so was to prevent educational research from interfering with normal classroom teaching. It was practically challenging to recruit all student participants from a single semester in the same class and then provide some students with access to CSA whilst offering other students with no access to CSA. In this latter situation, an education unfairness issue would also arise as all students should be treated equally.

6. Conclusions

This paper has described two computer simulation and animation (CSA) learning modules we recently developed to enhance student learning of force and acceleration in curvilinear motion in particle dynamics. Quasi-experimental, quantitative research has been conducted, involving a total of 286 undergraduate engineering student participants in the comparison and intervention groups. Based on non-parametric statistical analysis, it is concluded that both CSA learning modules developed in the present study are effective. Student participants in the intervention group achieved 44% normalized learning gain for CSA learning modules I and 40% normalized learning gain for CSA learning modules II. In contrast, student participants in the comparison group achieved only 15% normalized learning gain for CSA learning modules I and only 4% normalized learning gain for CSA learning modules II. The difference in normalized learning gains between the two groups is statistically significant.

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Ning Fang is Professor and Department Head of the Department of Engineering Education at Utah State University, U.S.A. He has taught a variety of courses at both graduate and undergraduate levels, such as Engineering Dynamics, metal machining, and design for manufacturing. His research in engineering education are in broad areas of engineering learning & problem solving, technology enhanced learning, and K-12 STEM education. His research in engineering focuses on the modeling and optimization of metal machining processes. He earned his PhD, MS, and BS degrees in mechanical engineering.

Yongqing Guo is a recent graduate of the Engineering Education PhD program at Utah State University, U.S.A. She earned a BS (2004) in civil engineering from the China University of Mining and Technology and an MS (2008) in civil engineering from the University of Idaho.