Piloting i-Newton for the Experiential Learning of Dynamics

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1.0 Introduction

Newtonian dynamics is the foundation for STEM education that starts in middle school and progresses through high school and college[1, 2]. A solid understanding of Newton's laws is critical for students pursuing degrees in engineering, physics[3], and chemistry, as well as in most life sciences[4]. Students seem proficient at reciting Newton's law with ease; however, few are able to apply these laws to natural and engineered systems. This disconnect in students' conceptual understanding may be linked to fundamental misconceptions of Newton's laws and to an abundance of overly fashioned examples[2, 5, 6]. Hands-on laboratories that feature real measurements could allow students to probe the dynamics of realistic systems, thereby strengthening their conceptual understanding[2, 7, 8]. However, the prohibitive cost of equipment and shortage of laboratory space limits these options.

Our project aims to overcome these challenges by utilizing a new, highly portable and inexpensive technology, which we call *interactive-Newton (i-Newton)*. The *i-Newton* can engage students in the experiential learning of dynamics outside the confines of the traditional lecture-based teaching methods.

The objectives of the project we describe in this paper are to:

1. Investigate whether *i-Newton* has an effect on students' conceptual understanding of the fundamental Newtonian concepts when compared to courses not using the intervention.
2. Determine whether *i-Newton* demonstrations affect students' self-efficacy, intention to persist in the major, and sense of inclusion.

2.0 Methods

The course ME240: Introduction to Dynamics and Vibrations is a required course at the University of Michigan for undergraduate majors in three programs; namely, Mechanical Engineering, Aerospace Engineering and Naval Architecture and Marine Engineering. The main units of the course cover topics in the three-dimensional motion of particles, the planar motion of rigid bodies, and elementary vibrations. This is a traditional lecture-based course offered in five large sections during the academic year and serving typically 400-450 students annually. Pertinent to this study, the course has no laboratory, partly due to its prior history as a lecture course but also due to the reality of the added expense and significant infrastructure that a companion-learning laboratory would require.

2.1 Participants

During one academic year, two *i-Newton* demonstrations were introduced into two of the five sections of ME240; students in those two sections comprise our two intervention groups. The other three course sections were taught in the traditional way, and students in those sections comprise the two control groups. Student enrollment for the control and intervention groups is included in Table 1.

Table 1. ME 240 student enrollment data: control and intervention courses

Fall 2013		**Winter 2014**	
Control #1	**Intervention #1**	**Control #2**	**Intervention #2**
61 (1 section)	149 (1 section)	174 (2 sections)	72 (1 section)

2.2 Survey Instruments

We hypothesized that *i-Newton* demonstrations would positively impact students' conceptual understanding, and we used a validated concept inventory instrument, known as the Dynamic Concept Inventory (DCI). The Dynamic Concept Inventory[9, 10] was created to assess students' understanding of concepts in rigid body dynamics, a major part of ME240. The DCI comprises 29 multiple-choice questions that map onto 14 of the most misunderstood concepts. The four *i-Newton* demonstrations included in this study were designed to reveal multiple DCI concepts.

We also hypothesized that the *i-Newton* demonstrations would increase students' self efficacy, defined as a person's beliefs of how well they can complete and execute a plan or goal[11, 12]. Instilling a strong self-efficacy comes from increasing one's knowledge and positive experiences associated with the outcome[11], so it is logical to expect that having a stronger understanding of the fundamental concepts may improve self efficacy Previous studies have examined self-efficacy in undergraduate students in regards to retention of women engineers[13, 14], career outcomes[15], and research-based teaching strategies[16, 17]. Finally, we hypothesized that *the i-Newton* demonstrations would positively impact students' intention to persist in the major and their sense of inclusion, and we used a modified version of the Longitudinal Assessment of Engineering Self-Efficacy (LAESE) to study these hypotheses. The LAESE is a validated 29-item instrument that measures four sub-factors: 1) engineering self-efficacy, 2) course specific self-efficacy, 3) intention to persist in the field, and 4) feelings of inclusion[13, 18].

For our study, students in all sections of ME 240 during the two terms of the project completed the DCI at the end of the term (allowing us to assess objective #1). Students also completed a modified version of the LAESE survey at the beginning and the end of the course (allowing us to assess objective #2).

2.3 i-Newton Demonstrations

The *i-Newton* is an innovative and inexpensive technology platform that stimulates learning of Newtonian mechanics. Utilizing new technology in the laboratory experiments to initiate engaged learning is beneficial[19, 20]. The technology behind *i-Newton* is a miniature inertial measurement unit (IMU) that measures the acceleration and angular velocity of any object to which it is attached; see example in Figure 1. For this study, we employed a commercially available IMU called the YEI 3 - Space sensor[21] (Yost Engineering, Portsmouth, Ohio), which incorporates a MEMS accelerometer (3-axis) and angular rate gyro (3-axis). The device measures angular rates up to 2000 $\frac{degree}{second}$, with 16-bit resolution, and a 0.03 $\frac{\frac{degree}{second}}{\sqrt{Hz}}$ noise floor and accelerations up to 12 g, with 14-bit resolution, and a 650 $\frac{\mu g}{\sqrt{Hz}}$ noise floor. Data was sampled at approximately 300 Hz, written to on-board flash memory, and subsequently downloaded to a computer via USB immediately after each demonstration. The data, which includes (3-D) acceleration and (3-D) angular velocity, can then be used to explore how concepts in dynamics are revealed in simple demonstrations and experiments that might be conducted live in class or by students outside of class (e.g., in a dorm room, coffee shop, hallway, outdoors, etc.). Doing so provides rich examples and real data for students to learn dynamics from a hands-on approach.

In our pilot, four experiments were designed for ME240 as in-class demonstrations led by the instructor. We expect to offer these as student-driven experiments in later terms. In the Fall 2013 term, two demonstrations were introduced 1) Oscillatory motion of a pendulum and 2) Rolling motion of a wheel. The following term, Winter 2014, two different demonstrations were introduced: 3) Jumping Motion of a Pogo stick and 4) Rotation of a Human Subject. In each term, the first demonstration illustrated concepts for the dynamics of particles, which is covered in the first-third of the course, while the second demonstration illustrated concepts for the dynamics of rigid bodies, which is covered in the second-third of the course.

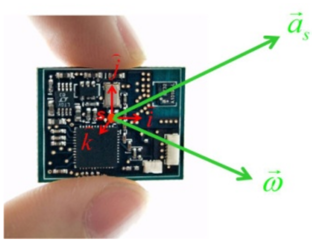

Figure 1: i-Newton is a highly miniaturized, wireless inertial measurement unit and transmits data for (3D) acceleration and (3D) angular velocity. When attached to an object, i-Newton therefore transmits the six-degree of freedom data needed to describe the complete (3D) motion of that object.

While space precludes a detailed description of all four demonstrations, we present one demonstration to illustrate how *i-Newton* was used and concepts probed by the recorded data in the Appendix A1.

2.4 Analysis

To address our first objective - to investigate whether *i-Newton* has an effect on students' conceptual understanding of the fundamental Newtonian concepts - we compared end-of-course concept inventory data for the intervention and control groups For each student, 14 separate concept scores were computed and compared for students in the intervention and control groups using an unpaired t-test. To address our second objective - to determine whether the *i-Newton* demonstrations affect the students' self-efficacy, intention to persist in the major, and sense of inclusion - we compared increases in LAESE scores from the beginning to the end of the term for students in our intervention and control groups. We compared the increases for students in the intervention and control groups using an unpaired t-test.

3.0 Results

Demographic data was collected from students during the first administration of our LAESE instrument at the beginning of the term. Of the 456 students enrolled, 371 students completed the pre-LAESE survey (response rate = 81%). Demographic data for these 371 students is shown in Table 3. There are no obvious differences in demographics for students enrolled in the control and intervention classes.

Table 3. Demographic Data for Students Completed the Pre- LAESE instrument

	Fall 2013		**Winter 2014**	
	Control #1 (N=25)	**Intervention #1 (N= 112)**	**Control #2 (N=162)**	**Intervention #2 (N=72)**
Gender				
Male	22 (88%)	90 (80%)	127 (78%)	52 (72%)
Female	3 (12%)	22 (20%)	35(22%)	20 (28%)
Ethnicity				
White, Not of Hispanic Origin	14 (56%)	73 (65%)	122 (75%)	48 (67%)
Asian	9 (36%)	31 (28%)	24 (15%)	16 (22%)
Hispanic/Latino	1 (4%)	3 (3%)	3 (2%)	5 (7%)
Two or more	0 (0%)	3 (3%)	5 (3%)	3 (4%)
Unknown/Do not wish to report	1 (4%)	2 (2%)	7 (4%)	0 (0%)
Black/African-American	0 (0%)	0 (0%)	1 (1%)	0 (0%)

A total of 24 and 142 students in the Control #1 and #2, 93 and 70 students in Intervention #1 and #2 completed the end-of-course DCI (response rates of 39%, 82%, 62% and 97% respectively). Because the LAESE instrument required completion at both the beginning and end of the term, response rates for the LAESE are lower: Control #1 and #2 had response rates of 13% and 79%, respectively. While the Intervention #1 and #2 had response rates of 48% and 85%, respectively.

3.1. Conceptual Understanding

We present the data for students in the separate intervention sections because the "topic" of intervention varied for students in the Fall 2013 and Winter 2014 (i.e., the specific concepts addressed in the two *i-Newton* demonstrations were different) with corresponding control sections. The average overall score and standard error for end-of-course DCI scores are 46% ± 1.4% for control #1, 51% ± 2.4% Control #2, 51% ± 1.7% for Intervention #1, and 46% ± 1.8% for Intervention #2. These scores are not significantly different (p-value #1 = 0.797 and p-value #2 = 0.621)

Only one of the fourteen DCI concepts for Intervention #1 had statistically significant difference when compared to Control #1. The score on concept 8 (zero velocity does not imply zero acceleration and conversely) for students in the Intervention #1 is statistically significantly higher than that for students in Control #1 (53% ± 3.9% versus 26% ± 6.0%, $p<0.0001$). This concept measures a student's understanding that: "An object can have (a) nonzero acceleration and zero velocity or (b) nonzero velocity and no acceleration." Though the concept isn't directly linked to either of the *i-Newton* experiments for that specific term, the concept was covered in the lecture and indirectly in both *i-Newton* experiments. Both experiments presented motions that were oscillatory (including times with zero velocity but non-zero acceleration and conversely). So the increase is not unexpected. Similarly, the score on concept 8 was statistically significantly higher for Intervention #1 then Intervention #2 (53% ± 3.9% versus 34% ± 4.4%, $p<0.0001$).

For all the fourteen concepts of the DCI there is no significant difference when comparing Intervention #2 to Control #2.

3.2 Self-efficacy, intention to persist, and sense of inclusion.

In the Control #1, only course specific self-efficacy showed significant differences between pre and post average scores with a p-value <0.0001. In Control #2, Intervention #1 and Intervention #2, there were no significant differences for all four factors when comparing pre to post average scores. Students in Control #2 exhibited significant negative gains for the course specific self-efficacy factor, while students in Intervention #2 demonstrated significant positive gains. These scores are statistically significantly different (-7.6% ± 2.1% versus 2.5% ± 1.2%; p<0.001).

4.0 Discussion and Conclusion

Regarding our first objective, the *i-Newton* demonstrations resulted in some significant improvement. For one of the fourteen concepts measured by the DCI, scores for the intervention group are significantly greater (Concept 8). Regarding our second objective, the *i-Newton* demonstrations similarly resulted in improvements. Students in the intervention groups demonstrated significantly greater levels of course self-efficacy. Thus, this pilot data suggests that *i-Newton* has the potential to increase student conceptual understanding of Newton's laws, depending on the concepts emphasized in the chosen experiments. The observed gains in Concepts 8 however might also be attributed to other differences in the course sections, including different emphases on concepts by the several instructors who participated. Thus an "instructor effect", uncontrolled in this pilot study, might also influence these gains.

The positive but modest trends above are perhaps unsurprising given the modest exposure students had to this technology in this pilot study. Thus, this pilot study did not exploit the full potential that *i-Newton* offers for true hands-on learning and exploration of dynamics both in and outside of the classroom. Achieving that exposure requires significant scaling of this pilot study to enable multiple student-directed experiments using this technology. The motivation for doing so is clear as revealed, for example, by Bandura[11], who demonstrates that hands on learning promotes increased student self efficacy.

In addition to demonstrating future potential, this pilot study also points to an obvious conclusion; namely, that *i-Newton* enables the experimental exploration of concepts associated with Newton's laws without the expense or infrastructure of the traditional brick and motor laboratory. The opportunity to create extensive hands-on learning (to complement traditional classroom instruction) with modest expense and no additional infrastructure cannot be over-emphasized. Moreover, we also learned that *i-Newton* can easily translate across disciplines for courses that emphasize Newton's laws, such as a course in Introductory Physics. As part of this pilot, we collaborated with an instructor teaching the laboratory section of Honor Physics (a small enrollment, first-year course at the University of Michigan) who deployed *i-Newton* extensively in prescribed laboratory experiments in addition to student-selected final projects. This greater level of exposure, which was immediately possible due to small class enrollment (approximately 20 students), is what will likely be required to reap the expected gains in using *i-*

Newton to increase student conceptual understanding, self-efficacy, intention to persist in the major, and sense of inclusion.

5.0 Acknowledgements

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Appendix

A1. Example of *i-Newton* Lab Experiment and Sample Results

Three frequently misunderstood concepts in the DCI for the dynamics of rigid bodies are that: (a) angular velocities and angular accelerations are properties of the body as a whole and can vary with time (refer to DCI Concept #3), (b) rigid bodies have both translational and rotational kinetic energy (refer to DCI Concept #4), and (c) points on an object that is rolling without slip have velocities and acceleration that depend on the rolling without slip condition (refer to DCI Concept #6). In addition, while not stated in the DCI, students frequently and mistakenly assert that mechanical energy is always conserved while in many (real) cases it is not conserved. A compelling experiment that students can perform on a bicycle wheel (obtained from their own bicycle or from one provided) nicely embeds all of these concepts.

Figure A1 depicts the front wheel of a bicycle with *i-Newton* mounted a distance r from the wheel center via a simple plate that spans the spokes. The IMU measures the angular velocity of the wheel as well as the acceleration sampled at the radial distance r. While there are a myriad of experiments one could perform using this simple set-up, a compelling experiment arises from first spinning up the wheel (while grasping the center axle), lowering it to a floor, and then releasing it. The subsequent rolling motion of the wheel on the floor is captured from the IMU’s angular velocity data and can then be exploited to understand fundamental concepts of rigid bodies concerning angular velocity, kinetic energy, rolling without slip, and mechanical energy.

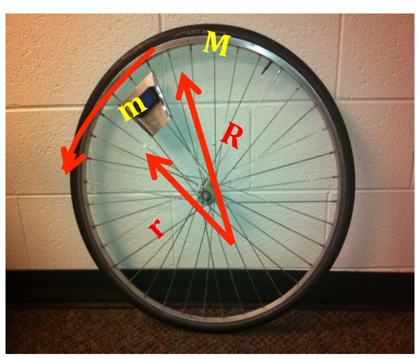

Figure A1. Experiment that explores multiple common misconceptions in rigid body dynamics by employing the wheel from a bicycle. i-Newton is depicted here (fastened a distance r from the *wheel center by a plate that spans several spokes) yields the angular velocity of the wheel as well as the acceleration sampled at the location of the sensor.*

For instance, Fig. A2 depicts the experimentally measured angular velocity of such a wheel rolling on the floor (three rolling cycles are illustrated). Notice immediately that, unlike idealized textbook problems, the measured angular velocity decreases about 5% over each cycle due to dissipation, which is so frequently ignored. In addition, the eccentric mass generates the observable sinusoidal variation as expected for a non-ideal wheel. To explore this further, our students were asked to compute and study the energetics of the wheel using numerical computations in Matlab ®. Starting from the measured angular velocity, our students computed the kinetic energy of the wheel (both translational and rotational components) and doing so made explicit use of the no-slip condition (equivalently, the concept of the instantaneous center of zero velocity). Next, our students computed the potential energy due to gravity (requiring first numerically integrating the angular velocity data), and then the total mechanical energy (sum of kinetic and potential energies). That sum immediately reveals that the mechanical energy decreases with each cycle (Fig. A2(b)). We further asked our students to reflect on this experimental fact and to propose the mechanism(s) responsible for this dissipation. This naturally led them to the phenomenon of rolling resistance of tires and the real (adverse) effects that rolling resistance has on vehicle energy consumption and greenhouse gas emissions! The point is that the four often-misunderstood concepts concerning the dynamics of rigid bodies were readily captured in this simple in-class experiment using *i-Newton*.

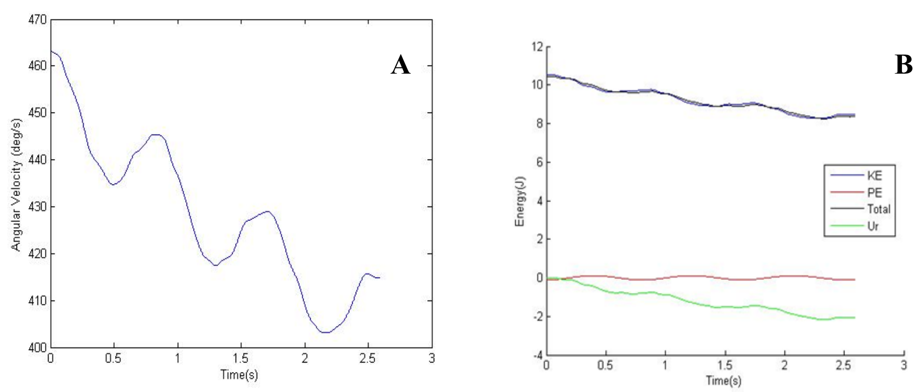

Figure A2. Experimental results for a bicycle wheel rolling across a floor. (a) The angular velocity of the wheel as measured by the attached IMU. (b) The energetics of the wheel as computed by the angular data including the kinetic energy (KE), the potential energy (PE), the total mechanical energy (Total), and finally the work done by dissipation (Ur).