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Designing At-home Laboratory Experiments Using Smart Phones and Basic Test Equipment for Senior Mechanical Engineering Students

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Abstract

A key educational component of laboratory experiments is the hands-on aspect: troubleshooting experimental setups, data collection and repeatability, honing data collection techniques to improve repeatability, and other forms of exploration and "learning by doing." With remote learning mandated by the global pandemic, students were unable to attend laboratory courses in person during the summer term of 2020 at The University of Pittsburgh. Thus, we developed a series of laboratory experiments for Mechanical Engineering seniors that could be done at home using simple, basic test equipment and also making use of the numerous sensors available in most smart phones. This paper will focus on the design and contents of these at-home laboratory experiments, the intended learning objectives, and discuss the strengths and weaknesses of each.

Three at-home experiments were designed with different learning objectives. First, a strength of materials lab, which incorporated the learning objectives of creating a test procedure, test repeatability, statistical data analysis, and test uncertainty analysis. Second, an acoustic reverberation time experiment, which incorporated the learning objectives of applying experimental test standards, creating digital filters, and performing spectral analysis. Third, a knee impact force lab, which incorporated design of experiments (DoE) and main effects analysis. The strength of materials lab required sending the students some basic test equipment, but the remaining two experiments primarily required the use of smart phone sensors and post-processing with various software. While the three at-home tests were fairly straightforward to complete, their procedural simplicity allowed students to collect data independently of their instructors with high enough data quality that analysis could be completed and understood. These three experiments were augmented with six fully on-line laboratories, where students watched videos and analyzed provided data.

Based on a qualitative examination and grading of the lab reports written by the students, all three at-home experiments were largely successful in teaching the expected learning objectives. The two experiments that relied mainly on the smart phone were more successful, in large part because they were procedurally simpler, and were successful enough that they will be included even in a non-pandemic academic term. Additionally, the logistics of sending equipment to students (and receiving it back from them) proved to be much more difficult than its added value justified. Thus, for future at-home labs we would focus only on using smart phone sensors and basic items that the students would be expected to have in their homes.

Introduction

The COVID-19 pandemic required an abrupt shift to online education in 2020, creating particular challenges in adapting laboratory classes that historically relied on specialized equipment and hands-on experiences. The hands-on experience is a particularly essential aspect of active learning for a laboratory course, as formalized by Chi's learning taxonomy, where interactive learning is preferred to either constructive or passive learning [1], or Kolb's Experiential Learning Cycle, which requires a balance of four abilities, including Active Experimentation and Concrete Experience [2]. Also, developing and conducting experiments are part of the ABET accreditation outcomes, which can most effectively be addressed through direct, hands-on experimentation [3]. Furthermore, some research has shown that online-only courses can suffer from a lack of application-based learning, particularly for laboratory skills [4].

In the Summer term of 2020 at The University of Pittsburgh, Mechanical Measurements 2, a senior-level undergraduate mechanical engineering course focusing on experimental methods and data analysis, was taught fully online instead of in-person. The goals of this course are to teach students about ABET outcomes 1-3, 5, and 6: experimental planning and design, interpreting data by selecting suitable analysis methods (statistical, frequency domain, filtering, appropriate data presentation), and drawing conclusions, as well as broader outcomes such as verbal/written communication skills, working in teams, and professionalism [5]. The course had 40 students with a weekly two-hour lecture led by the course instructor and a two-hour laboratory section led by graduate teaching assistants (TAs). The laboratory experiments for this course historically used specialized, stand-alone test equipment, such as a tensile test machine or a steam engine, to conduct particular experiments. These experiments could not be easily replicated by students at home, so six of these experiments were chosen to be "online only", whereby students watched videos of experiments being conducted, viewed presentation slides, and analyzed provided data. However, this emphasized the "procedural" aspects of the experiments and eliminated the critical hands-on aspect, thereby losing the inquiry and discovery elements of a typical laboratory class [5]. Thus, these six online experiments were augmented with three, newly-developed at-home laboratories using either simple equipment that the students could be sent (or purchase inexpensively) and also using the numerous sensors available in a typical smart phone.

Replacements for in-person, hands-on laboratories have been developed for various reasons: to allow for online learning and geographic disparities, as well as cost savings to reduce the investment in laboratory equipment and lab space. The common options to replace in-person laboratories include: (1) simulated labs, using software and physics models to replace the laboratory equipment [2]; (2) remote labs, where the students control the laboratory equipment via computers [6], [7]; and (3) at-home labs, where the students use basic equipment or easily accessible or built equipment to complete hands-on laboratories, but in their own living spaces. The simulated and remote laboratories have been shown to provide some similar benefits to in-person labs, such as becoming familiar with processes, recording information from gages or readouts, connecting a process to the "sensor" observations, and collecting data. However, virtual labs also have limitations, such as not engaging students in physical experimental setup (connecting sensors and signal conditioning electronics), practical aspects of trouble-shooting an experimental setup (a realistic aspect of experimentation), and developing the confidence of setting up and working with real experimental equipment. These shortcomings can be overcome by the at-home labs, as seen in [4], where basic equipment is sent to students to use at home, or in [8], where programmable logic boards were used for a digital design lab. Others have developed fundamental science experiments that would only require materials and equipment that are typically already available in the home, such as physics labs [9] and performing chemistry laboratories using home equipment [10].

A subset of at-home laboratories have been designed to use the sensors available in smart phones [11], for example to demonstrate classical concepts in physics (e.g., the period of a simple pendulum). A modern smart phone has a tri-axial accelerometer, sound recording capability, a light meter, GPS, a magnetometer, and other sensors that can be accessed using freely downloadable apps. Also, smart phones are nearly ubiquitous amongst the student population in a typical university in the US. Drawbacks have been noted in previous studies, including that the smart phone is both sensor and display, meaning that the data often cannot be viewed while it is being taken, and data typically must be later analyzed on a computer [11].

While the absolute accuracy of the smart phone sensors can vary, and they are also difficult to calibrate, the experiments were designed to emphasize learning objectives that were independent of the sensor accuracy and also appropriate for senior mechanical engineering undergraduates, including test procedure development, uncertainty analysis, Design of Experiments (DoE), the use of test standards, and the development of MATLAB tools for data analysis. Additionally, the uncertainty of the sensors in the smart phones can serve as an inroad for exploring test uncertainty and the potential for improving the test methodologies.

Methods

Before designing the three "at-home" experiments, a survey was sent to students to identify what equipment they had available and what equipment would need to be provided to them. The survey also confirmed that all students had a smart phone with the required sensors.

Prior to performing each at-home lab, part of the lecture period was used to discuss key theoretical and procedural aspects. During each at-home lab, students would log into a Zoom meeting with their lab section and a graduate TA. The students were then separated into smaller, 3- to 4-person lab groups to discuss their procedures and results, and the TA was available to assist and answer questions. Assessment was conducted via lab reports written by each student, with discussion questions including specific areas where the students should consider whether the simple equipment and phone sensors were sufficient to conduct these particular tests, and how to improve these tests in the future (e.g., by using purpose-built lab equipment).

Three mechanical engineering topics were covered in the at-home labs: solid mechanics via beam bending theory, room acoustics and measurement, and dynamic force measurements. The solid mechanics lab was developed to use simple equipment sent to the students, whereas the other two used only the smart phone and supplies that a typical student would have in their residence. The other requirements for the newly-developed laboratories were as follows: no safety concerns, the ability to be conducted by any of the students on their own, and the inclusion of one or more specific topics covered in lecture material. Each of these labs is described in the following subsections.

Strength of Materials Experiment

The strength of materials lab was based around the idea of performing material property characterization (elastic modulus and tensile strength) using simple equipment in lieu of expensive laboratory equipment, such as a tensile test machine. The key learning objectives were to apply design-stage uncertainty analysis, calculate actual test uncertainty from multiple trials, and use these calculations to evaluate the efficacy of the test procedure and suggest improvements for the test. Additional learning objectives include employing creativity and ingenuity in using materials around them to complete the assignment.

The test involved clamping a beam-shaped specimen to a table, incrementally adding force to the tip of the beam and measuring tip deflection, then ultimately breaking the beam with a known force. By using theoretical beam bending equations from solid mechanics and the measured dimensions of the beam, the elastic modulus and tensile strength of the material could be calculated.

The required equipment included a small laboratory or kitchen scale, calipers, and a small bar clamp. This equipment was either already possessed by the students, purchased by students (and they were reimbursed), or mailed to them from the University. The remaining items (wire, plastic bottle, tape) were assumed to be easily obtained by the students. Chopsticks were chosen for the test specimens as they are inexpensive, fairly uniform in dimension, and available in different materials (e.g., birch wood and bamboo). These were mailed to each student with their equipment.

The procedure given to the students was highly detailed to improve repeatability, including instructions on how long to make the specimens, how to mount the beam to the table, where to apply the force, and how to measure the dimensions of the specimens (as the chopsticks had a non-uniform cross-section along the length). A second, unloaded test specimen was mounted next to the loaded specimen for the purpose of measuring relative deflection, as shown in Figure 1.

The bottle was hung from the tip of the beam and filled with increasing amounts of water to apply the known input force. The deflection was measured at various stages after force was added. Finally, water was slowly added until failure of the beam and the final weight of the filled bottle was measured. This procedure was followed for all test samples (two wooden chopsticks and four bamboo chopsticks).

Figure 1 – Mounting and loading beam specimens for the Strength of Materials at-home lab

The students used the beam dimensions, applied force, and deflection measurements to calculate the elastic modulus and ultimate strength for each sample using Equation 1.

$$y = \frac{FL^3}{3EI} \tag{1}$$

Where:

- y – tip deflection (m)
- F – point load (N)
- L – beam length to point load (m)
- E – beam elastic modulus (Pa)
- I – cross-sectional moment of inertia (m^4)

The results from each person in the lab group were pooled together to generate a larger sample set. The results were averaged for each material (birch wood and bamboo) and test uncertainty was calculated to +/- two standard deviations from the mean. These experimental results were compared to expected values of elastic modulus and tensile strength that the students had to research from references.

The students also calculated design-stage uncertainty for the failure test using the beam stress equation (Eq. 2) as their governing equation. As inputs to the uncertainty analysis, the students were required to estimate the individual uncertainties of each variable: beam dimensions, elastic modulus, and applied force.

$$\sigma = \frac{M\left(h/2\right)}{I} \quad (2)$$

Where:

σ – stress (Pa)
M – bending moment (N-m)
h – beam thickness (m)

For discussion, they compared the design-stage uncertainty with the experimental uncertainty, as well as comparing their experimentally-determined material properties to the expected results from literature. Finally, the students discussed the efficacy and appropriateness of the test procedure and suggested changes to improve the test procedure.

Reverberation Time Lab

In the Reverberation Time Lab, students measured the acoustic reverberation times of a room in two states: either relatively empty or with added materials to absorb sound. The reverb time was calculated using both the full bandwidth recorded signal and a filtered signal using the standard 250 Hz octave band. The learning objectives were to: 1) Read and apply key, excerpted aspects of a test standard (in this case, ISO 3382-2 [12]); 2) Adapt a test standard to an at-home environment and identify key differences with the test standard; 3) Record acoustic data and perform simple processing using MATLAB to calculate the reverberation time of a room; 4) Design a digital bandpass filter to filter data into the 250 Hz acoustic octave band [13]; 5) Generate conclusions on the acoustic absorptivity and reflectivity of various materials; and 6) Integrate laboratory experiments with everyday life (thinking about sound reflectivity and sound absorption as it relates to materials in the home, such as tiled versus carpeted floors).

The tests involved generating an impulsive sound source within an enclosed room, and measuring the decay of that sound over time. Students were directed to find a naturally reverberant room, such as a bathroom or garage. For the empty state, students were instructed to remove any sound absorbing materials and for the other state, students were advised to add as many absorptive materials as practicable, particularly to cover wall and floor surfaces. Providing that a significant absorptive surface area is created, students should easily see a measurable difference in reverberation time between the two states of the room, particularly in the higher-frequency octave bands.

The required materials for the lab included: 1) a smart phone with a sound recording app (e.g., Hi-Q MP3 Voice Recorder), 2) a reverberant room in a home (bathroom or garage), 3) sound absorbing materials that can be added and removed from room (towels, carpets, curtains, blankets, etc.), and 4) MATLAB with the Signal Processing Toolbox for filtering and data analysis, 5) an impulsive sound source, such as a balloon pop or hand clap.

The lab handout included basic acoustic theory, including for room acoustics, an explanation of reverberation time, and how to compute instantaneous sound pressure level, $SPL(t)$, from the measured acoustic pressure, $p(t)$, in accordance with equation (3).

$$SPL(t) = 20\log_{10}\left(\frac{p(t)}{20\times10^{-6}}\right), \quad dB. \tag{3}$$

The graph in Figure 2 shows the instantaneous SPL when a continuous sound source is permitted to build up to steady state and then abruptly shut off at time = 0. Since students are unlikely to be able to produce a spectrally white, continuous noise source, the "impulse method" was used, whereby the decay of a loud pop is measured. In either case, when the envelope of the sound level, $SPL(t)$, is plotted using the logarithmic decibel scale as in Figure 2, its exponential decay is approximately a straight line. Reverberation time, T_{60}, is defined as the time required for sound to decay by 60 dB. Since very loud noise sources are required to produce sound more than 60 dB above the noise floor, the time to decay by 30 (T_{30}) or even 20 (T_{20}) dB is measured instead, and extrapolated to T_{60} by multiplying by 2 or 3, respectively. One advantage of this at home lab is that calibrated microphone signals are not required, since only the relative sound level is required to calculated the decay time.

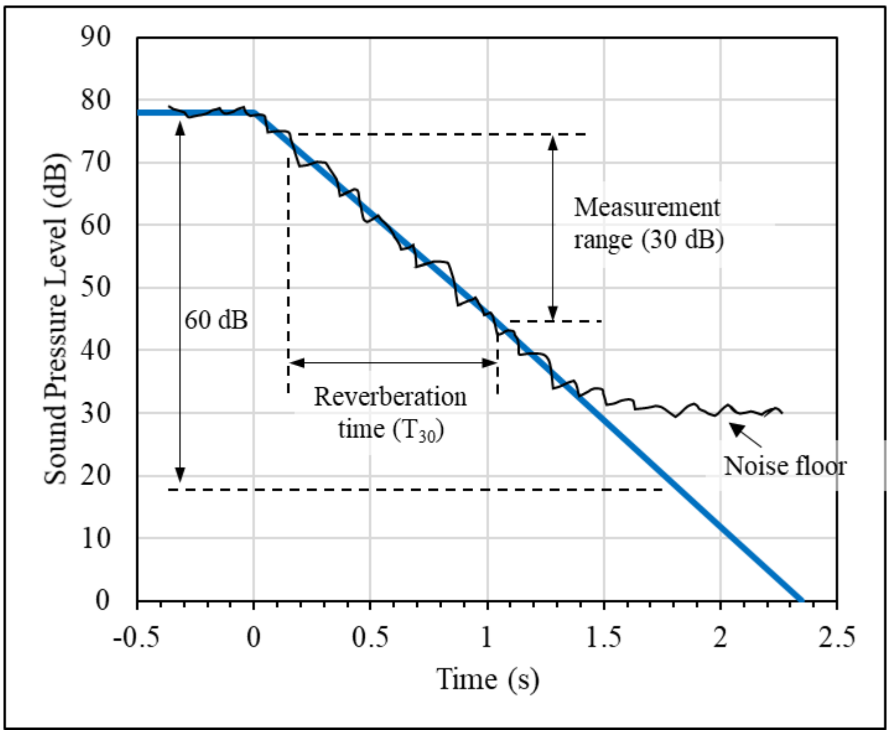

Figure 2 – Plot showing to use the envelope of sound pressure level to compute T_{60} (the time for sound to decay by 60 dB) from a T_{30} reverberation time [12].

Examples of reverb times for various listening environments were given in a table that ranged from broadcast studios ($T_{60} = 0.5s$), to lecture rooms ($T_{60} = 1s$), to cathedrals ($T_{60} = 3s$). Students were given a table of standard 1/1-octave band frequencies used for acoustics. The project provided the opportunity to use one of the tools taught in the course lecture: creating a digital Butterworth bandpass filter using MATLAB. The 250 Hz band was chosen as a nice compromise of being low enough frequency to decay more slowly, while being at a high enough in frequency to be excited by the impromptu acoustic impulse, as well as being influenced by the absorptive articles introduced into the room.

Students used the MKS Sabine equation (4) to calculate average room absorptivity, $\overline{a}$, based on room volume, V, and surface area S, and the reverberation time, T. A table with absorptivities for common materials for each octave band between 125 Hz and 4kHz was also supplied. The lab handout also contained step by step measurement instructions for the students, however it was up to them to choose a recording app, select a room where they live, and choose sound-absorptive articles to be added or removed from the room.

$$T = \frac{0.161V}{S\bar{a}} \tag{4}$$

Post-processing in MATLAB was used to estimate the T_{60} from the recorded waveforms. Given the complexity of this step, a 20-minute supplemental video was created to walk students through the process, which included how to read an audio file, scaling the data, plotting the data and identifying the noise floor and hence the region to curve-fit, how to choose whether to compute T_{20} or T_{30} depending upon the signal to noise ratio, and conditioning the data to perform the linear curve fit to determine T_{20} or T_{30} using the slope of the decay of the sound pressure level. Students used the curve fit line to determine the times to decay by 20 and 30 dB, which in turn are used to extrapolate to T_{60}.

In their reports, students were requested to explain basic room acoustics theory, a description of the room and absorptive treatments, the type of impulsive excitation, plots of the raw waveform, plots of the envelope of sound pressure level that include the curve fit, their 250 Hz octave band filter design, the rationale for selecting the portion of their curve for a curve fit, and to compare the measured and calculated reverb times for the room with and without treatments and with unfiltered and filtered signals. It was suggested to repeat each test case at least twice. Students were expected to come to the realization that the bandpass-filtered waveform has lower amplitude than the raw waveform because part of the signal energy has been filtered out, and to recognize that this would complicate computing T_{30}, requiring them to create a curve fit over an even smaller decay interval (e.g., T_{15} or T_{10}) and interpolate accordingly.

Knee Impact Force Experiment

The key learning objectives of the knee impact force experiment were to implement a formal Design of Experiments (DoE) as a full-factorial design to investigate factors that would affect the impact force seen by a human knee joint during walking or running. The students then calculated main effects and interactions between the test variables. Secondary learning objectives were to have students investigate methods for fixturing the sensor to the leg of a test subject.

The only equipment required for this experiment was a smart phone with a triaxial accelerometer, an app to access and record the accelerometer output (e.g., Physics Toolbox Sensor Suite [16]), and some tape or elastic bands to secure the phone to the leg of the test subject. The phone's accelerometer was used to calculate the g-force experienced by the lower leg during walking or running. This type of test was appropriate for the accelerometer in a typical smart phone, as the maximum expected acceleration is less than 20 g's and a low sampling frequency (400 – 500 Hz) is sufficient to capture the data.

The students had to investigate their own methods to secure the phone to the lower leg, though some guidelines were given. For example, the phone should be attached as rigidly as possible, to the front or side of the shin, without fabric between the phone and the leg. They were required to discuss the methods and reasoning for the fixturing of the sensors in their lab reports.

Students were prompted to select three variables to study that could affect the impact force on the lower leg, which would be transferred to the knee. Example variables were: stride length (distance between foot strikes), insole use/type, foot strike position (gait), shoe type/sole material, and running/walking velocity. The students chose two levels for each variable, created a full-factorial DoE for their test, and justified their selections of variables and levels. An example DoE is shown in Table 1 below. The three factors shown in the table are whether an insole is present (yes/no), the running style/gait (heel strike/toe strike), and the stride length (short/normal).

Table 1 – Example full-factorial test matrix for Knee Impact Force experiment

	Factors		
Test #	*Insole*	*Gait*	*Stride*
1	Yes	Toe Strike	Short
2	No	Toe Strike	Short
3	Yes	Heel Strike	Short
4	No	Heel Strike	Short
5	Yes	Toe Strike	Normal
6	No	Toe Strike	Normal
7	Yes	Heel Strike	Normal
8	No	Heel Strike	Normal

For each experiment in the DoE, the test subject walked or ran for 15-20 strides on the tested leg while data was being recorded. Because the peak accelerations can vary widely, the six highest accelerations from each experiment were selected and averaged to represent the "peak" acceleration. These were put into the DoE results matrix, where the main effect of each variable was calculated as well as the interactions between variables. The students were required to discuss these results and their broader meaning in terms of ways to reduce knee impact forces while exercising. The students were also required to suggest ways to improve the test.

Results

Example results from each at-home experiment are shown in the following subsections. Also, recurring discussion items mentioned in the students' lab reports are highlighted for each experiment. Comments on the ability of the at-home labs to achieve learning objectives will be placed in the Discussion section of this paper.

Strength of Materials

The results from ten students were aggregated into Table 2 below to give an idea of typical results. Note that the "expected" results were researched by the students and could vary by up to 20%, depending on the source of information used.

Table 2 – Example Experimental Results from Strength of Materials Test

	Wood (Birch)	Bamboo
Mean Elastic Modulus (GPa)	7.8	11.7
Test Uncertainty (GPa)	+/- 3.4	+/- 6.1
Expected Elastic Modulus (GPa)	10.0	12.7
Mean Tensile Strength (MPa)	109.9	242.9
Test Uncertainty (MPa)	+/- 36.2	+/- 136.2
Expected Tensile Strength (MPa)	91.9	190.9

For these aggregated results, the mean experimental results from the aggregated data for elastic modulus and tensile strength were within 7-27% of expected (literature) values. However, two-sigma experimental uncertainties ranged widely: 33-56% for the aggregated results (though some students reported experimental uncertainties up to 100%).

Student were required to submit their measurement files, lab reports and their analysis files (MATLAB and/or MS Excel). In their lab reports, multiple students discussed the following items related to the learning objectives of test uncertainty, design-stage uncertainty, and test procedure development. They successfully noted that the design-stage uncertainty was smaller than the actual test uncertainty for reasons of both mismatch between the theoretical model and reality and due to human error. Most students recognized that their calculation of bending moment of inertia was an over-simplification, due to the chopsticks having non-uniform cross sections. A subset of students surmised that this would mean their experimental results should create a lower bound as compared to the expected results. Many students also recognized the difficulty in accurately measuring small deflections using their simple equipment. Multiple students noted that the single clamp to hold the test specimen was not sufficient to provide a true cantilever boundary condition.

For the test procedure, the students had multiple recommendations to improve the test. First, to use multiple clamps to clamp down the entire length of the beam on the table to more accurately model a cantilever beam. Second, to use more geometrically consistent, non-bowing objects rather than chopsticks, e.g. pencils made of wood. Third, the need for a more precise way to accurately measure small deflections. Lastly, to use a more accurate moment of inertia calculation, such as using a compound moment of inertia using a combination of shapes, to better represent the cross-section of the beam.

Reverberation Time Experiment

Most student created tables similar to Table 3 reporting their measured T_{20} times and extrapolated T_{60} times for the four test cases.

Table 3 – Example Table Showing RT60 Calculations for Unfiltered and Filtered Empty and Full Rooms

RT60 Determination		
	RT20a (s)	**RT60 (s)**
Empty, Unfiltered	0.267	0.800
Empty, Filtered	0.272	0.816
Full, Unfiltered	0.162	0.485
Full, Filtered	0.215	0.644

In addition, as requested, students included figures of the signals for comparison. Figure 3 shows the raw and curve-fitted waveform for an empty room from one student group, while Figure 4 shows the same for the room that has had absorptive articles introduced.

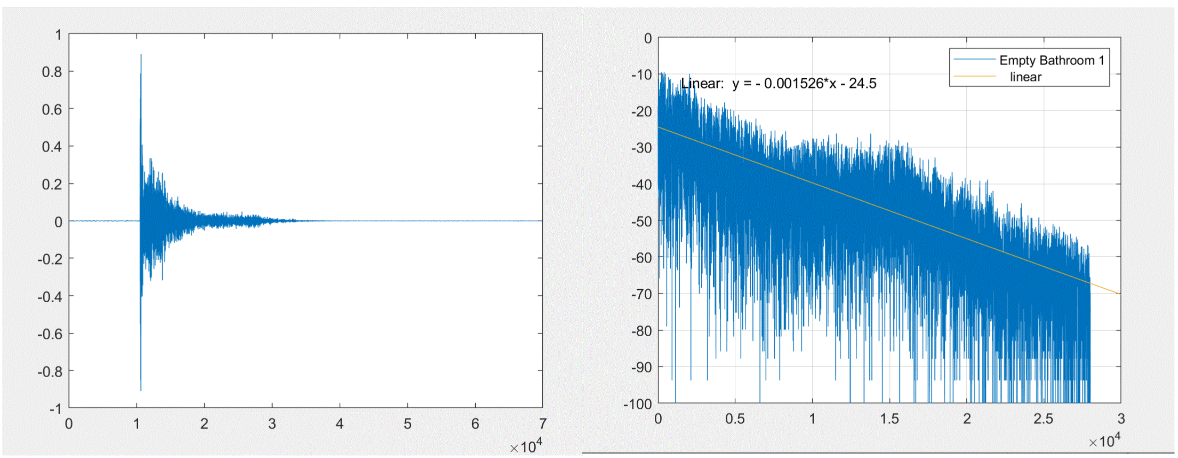

Figure 3 – A student's raw (left) and curve-fitted (right) signals for an empty room. The left figure is amplitude versus time and the right figure is magnitude (dB) versus time.

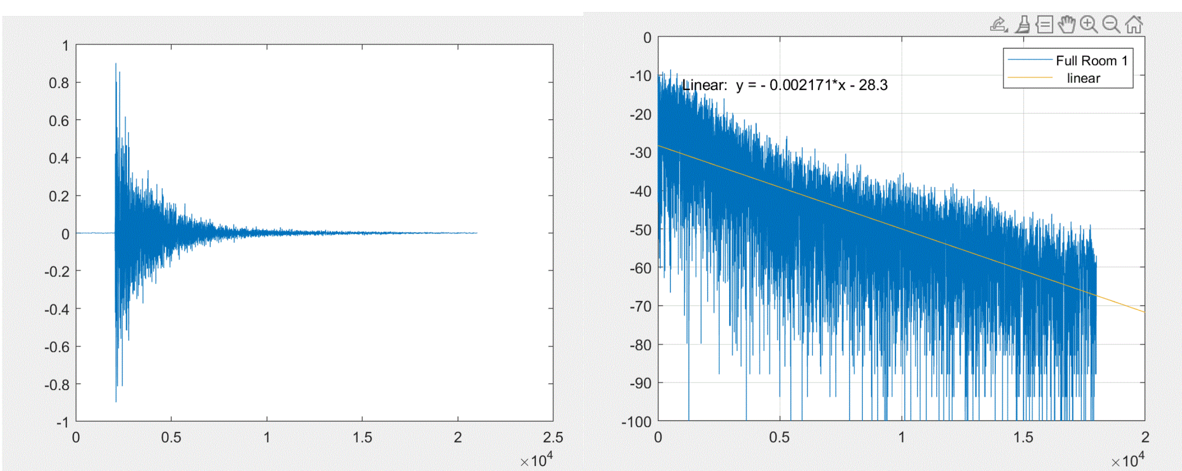

Figure 4 – A student's raw (left) and curve-fitted (right) signals for a room that is filled with absorptive articles. The figure on the left are amplitude versus time and on the right is magnitude (dB) versus time. Please note the different time scales in the raw signals Figures 3 and 4.

Knee Impact Force Experiment

Representative raw test results for one trial in the knee impact force experiment are shown in Figure 5 below. The results show the g-force recorded during strides from a test subject running on concrete. The peaks in the data show the peak acceleration recorded at the lower leg for each stride of the foot.

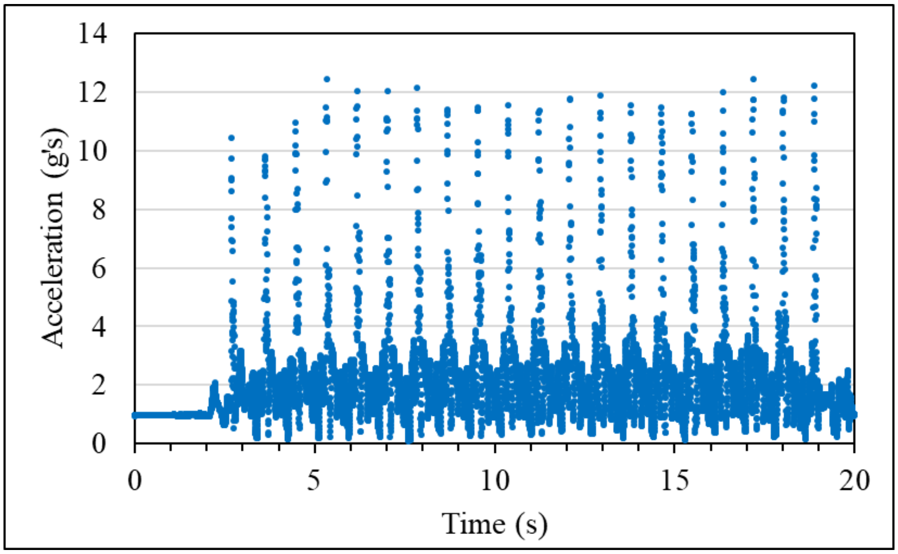

Figure 5 – Example acceleration data plotted from one knee impact force test

Once the acceleration data was collected, average results were calculated, with representative data shown in Table 4.

Table 4 – Example averaged acceleration results in a full-factorial DoE table

	Factors			
Test #	**Insole**	**Gait**	**Stride**	**Average Acceleration (g's)**
1	Yes	Toe Strike	Short	7.7
2	No	Toe Strike	Short	9.2
3	Yes	Heel Strike	Short	10.5
4	No	Heel Strike	Short	11.0
5	Yes	Toe Strike	Normal	8.0
6	No	Toe Strike	Normal	9.9
7	Yes	Heel Strike	Normal	10.7
8	No	Heel Strike	Normal	12.2

From these, main effects and interactions between the various factors could be calculated, with an example shown in Table 5.

Table 5 – Example main effects and interactions from acceleration results

Factor	Main Effect (g's)	Factors	Interaction (g's)
Insole	1.4	Insole x Gait	-0.3
Gait	2.4	Insole x Stride	0.3
Stride	0.6	Gait x Stride	0.1

Regarding the Design of Experiments learning objectives, all students' lab reports showed that they successfully acquired data and were able to generate results that had trends matching their intuition on the main effects of each selected factor (e.g., faster running velocity caused an increase in measured impact force). When calculating the variable interactions, the results were less intuitive, with some variables showing strong interactions and others no interaction. These results led to multiple students indicating that they wished to take additional data for certain variables at additional levels.

As for the sensor fixturing and improving the test procedure, multiple students discussed the following items. First, that variations in sensor fixturing between trials were difficult to assess, and developing a more secure method to mount the smartphone to the test subject's lower leg would be beneficial. Second, that the procedure should require a large test area (long path) to get the number of strides requested and that it should be a hard, flat surface to reduce variability between trials. Lastly, that some variables (e.g., running velocity) were not quantitatively measured, which could create error and variation between trials.

Discussion

For each at-home laboratory, we will discuss the following:

1. Achievement of learning objectives
2. Ability of students to collect reasonable data
3. Feasibility of doing each lab at home
4. Improvements and changes to individual labs if continued in the future
5. Whether these should be implemented in a non-pandemic situation.

Strength of Materials Experiment

Reviewing the students' lab reports showed that they were moderately successful in achieving some of the learning objectives, while having less success in others. For the raw data, students were able to successfully capture data and calculate results, and average experimental values calculated were generally within 20-30% of published values, with better accuracy for Elastic Modulus than Tensile Strength. However, experimental uncertainties ranged widely: typically 40 - 60% of the mean values for two standard deviations. This could likely be due to the pooling of data from multiple students to achieve a data set, as different procedures by particular students can create outliers, leading to wide-ranging results.

However, these wide-ranging results proved to be a useful outcome in the learning objective to develop and improve a test procedure. Students generated good insights into why the at-home experiment had high uncertainty, including the difference between their calculation of moment of inertia and the actual moment of inertia for these non-uniform beams. Additionally, some students recognized that wood and bamboo can be naturally highly variable in their properties. However, only a few realized that pooling their data caused an increased chance for human error and repeatability issues. Also, few students realized that the extreme beam deflections meant that the test deviated from the assumed small deflections in the theoretical beam bending equations. This assumption for the theoretical equation could be emphasized more in the lab handout used by students to conduct the experiment.

Many students calculated test uncertainty but failed to complete the Design-Stage Uncertainty analysis, which could indicate a lack of understanding of the difference between calculated experimental uncertainty and design-stage uncertainty. If this experiment is used in the future, this distinction should be addressed more clearly in the laboratory handout and also by the TAs during the actual lab time.

From a pragmatic standpoint, sending and receiving the test equipment was logistically difficult, requiring significant work from the instructional staff. Some students received equipment late and ended up improvising with less-effective materials. Also, requiring students to mail the equipment back and request reimbursement for the postage took additional time and effort. Combining these logistical issues with the only moderate achievement of the learning objectives, we do not plan to run this experiment during a non-pandemic academic term. It's possible that we could modify the laboratory to be more successful in an in-person setting, but we would likely improve the test procedure and equipment used.

Reverberation Time Experiment

Most students were successful at all of the learning objectives for this experiment. Students were able to select an appropriate room where they could record acoustic impulses which in turn were used to find the reverb times. All students reported differences in reverb times between the filled and unfilled rooms. In some cases the difference in T_{60} was a factor of two (2) or more. The reverb times ranged in general between and 0.25 and 1.1s, but in general the empty rooms typically produced a reverb time of around 0.4-0.5s and the filled rooms were generally between 0.6-0.8s. Given that many students chose smaller, reverberant rooms (bathrooms), this typical range of reverberation times seems completely reasonable, while 0.25s and 1.1s are extreme. In fact, reverb times above 0.8s were typically the result of improperly choosing the curve-fitting region during post-processing. For the filtered waveforms (250 Hz octave band), they typically had significantly longer reverb time (up to 50% higher). Again, this result is expected, given the nature of damping, where energy in the frequencies in the higher octave bands decays much more quickly than that at lower frequencies.

Some students struggled in choosing the appropriate region to curve fit, which should have been "well above" the noise floor – perhaps at a signal to noise ratio of at least 10 dB, if not higher. The largest error was from a student group that used a continuous noise source for the measurement, where they included the steady-state portion of the signal (time less than $t = 0$ in

Figure 2), which drastically impacted the results. The instructional video provided to guide the students only included examples of how including regions with too much noise can impact the T_{60} calculation.

Students conducted each measurement a minimum of three times and were generally good at recognizing any outliers in their T_{60} results. Given that mechanical engineers are not always fond of signal analysis, the reports generally showed better than expected mastery of the required data analysis tools, perhaps in part because of the instructional video and lectures focused on digital filtering. Most students successfully identified limitations in their methods as compared to the ISO test standard, namely lack of omnidirectional microphones, not using multiple impulse and measurement locations, and not meeting the required spacing between the microphone and source (typically a hand clap) as a result of, e.g., using a cramped bathroom. A small number of students reported that they measured in accordance with the standard, which of course is not correct.

Knee Impact Force Experiment

Teaching Design of Experiments in a lecture setting is often confusing for many students, particularly as the ultimate purpose of the DoE is lost in the mathematics of calculating the results. Choosing an experiment where the students have some intuition about the results, as walking and running are everyday activities for most of them, allowed them to be able to successfully design their full-factorial DoEs and select reasonable levels for each variable. Likewise, the calculated main effects were typically intuitive and matched the students' expectations; for example, increasing running velocity leads to higher impact forces. This matching of expectations can lead to a deeper understanding of how to understand the main effects analysis as compared to an experiment where the outcomes are not intuitive from the outset. Furthermore, the calculation of interactions was sometimes intuitive and sometimes counter-intuitive, leading some students to wish to investigate further and perform more testing in specific areas. This is an excellent extension of understanding the purpose of a DoE: to efficiently cover a wide range of the potential experiment space in order to determine the best areas for further study.

While the quality of the data ranged amongst the students, many of them recognized some of the key problems with accurate data collection. First, that their method for fixturing the phone to the leg could be improved and standardized to improve repeatability between trials. Second, that their selection of levels for each variable required the levels to be distinct enough to see a clear result in their analysis. (For example, some students chose "Shoe Type" as a factor, but selected shoes that were fairly similar, e.g., a running shoe and a basketball shoe). Both of these aspects, which could be seen as detriments to the outcome of the lab, were actually strengths as students learned to think critically about the design of the experiment and how to improve it.

Overall, most students achieved all of the learning objectives for this experiment. The intuition and learning developed by the students and expressed through their results and reports were shown consistently across all of the submissions. Thus, this experiment would be useful, even in a non-pandemic situation where the students have access to a laboratory. In fact, this experiment could even be more useful in an in-person group setting as students could share "best practices" in fixturing the phone to the leg, as well as running the experiment with the same variable choices and comparing results.

A useful improvement to this laboratory for the future would be to use the free *phyphox* app developed by Staacks et al. [11]. It would allow remote access to the phone's sensors through a computer as well as real-time display of data, thus eliminating the need to remove the phone and re-secure it to the leg and also let the students check the quality of their data and decide whether to take additional data.

Conclusions

The at-home laboratory experiments were largely successful in achieving their learning objectives and engaging the students in hands-on studies to augment online laboratory experiments. Two of the three experiments were successful enough that they will be considered for inclusion even in a non-pandemic academic term. The laboratories that relied mainly on the smart phone were most effective in achieving their learning objectives, and also had fewer logistical issues, including no requirement to send or receive equipment. Thus, building the at-home laboratories exclusively around the smart phone sensors and simple supplies that the students already have is the most effective way to run these at-home laboratories.

In fact, the simplified procedures for the at-home labs and requirements for students to creatively provide some materials led to a more interactive and discovery-based learning experience, even compared to the typical laboratories that were done "in person" during a non-pandemic academic term. Thus, we are considering including some of these laboratories during the in-person course, as well as modifying other existing laboratories to include some of these discovery and inquiry aspects.

Overall, this experience indicated that the quality of the sensors used can be a secondary consideration for an educational laboratory, if the learning objectives are focused on the qualitative aspects of laboratory experiments and the data trends are clear enough that quantitative analysis can still have intuitive outcomes.

Copies of the handouts for each laboratory are available from the authors upon request.

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