STAYING CURRENT

Smartphone-assisted experimentation as a didactic strategy to maintain practical lessons in remote education: alternatives for physiology education during the COVID-19 pandemic

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INTRODUCTION

Online and distance education are very popular, and the number of students taking a distance course is steadily growing (33). However, a critique we often hear from fellow university instructors toward online undergraduate courses in biology is that they are less effective due to the lack of laboratory classes. Several didactic strategies can be applied to overcome this obstacle, such as the following: virtual laboratories, laboratory videos, kitchen laboratories using household items, and laboratory kit activities sent to students by regular postal service (39). Despite these strategies, teaching through experiments can be challenging for both students and instructors in the context of online and distance education.

The number of online resources for teaching biomedical disciplines is extensive. However, the didactic tools available for hands-on activities in physiology are not as common as those for activities in anatomy and histology. Virtual atlases and interactive videos for anatomy education are effective at promoting engagement and learning (12, 36). Similarly, the virtual microscopy and histology slide collection is an effective tool for distance education and blended learning, where students can achieve similar performances as their peers in the face-to-face (F2F) format (2). Interestingly, students seem to prefer the online rather than the F2F format (42). Because anatomy and histology are morphological sciences, the use of augmented and virtual reality are additional didactic resources that facilitate the engagement of students in manipulating and understanding body structures (5). Contrary to anatomy and histology, physiology learning is concerned with understanding the dynamics and mechanisms of variables of the human body. Teaching such mechanisms only with static images may give the novice physiology student the impression that these mechanisms are rather straightforward and simple rather than complex and dynamic. Moreover, the experimentation in physiology education is dependent on data collection, which requires expensive laboratory equipment. Thus, while students can perform hands-on activities at home to learn anatomy and histology by using virtual atlases and microscopy, respectively, to learn physiology by practice, students would be necessarily dependent in principle on institutional facilities. However, for certain physiology contents, computer-based simulators can assist in experiments at home.

To inspire educators to develop assignments and apply experimental physiology activities in distance education, despite the lack of specific laboratory facilities in the homes of students, we present herein the rationale of mobile learning laboratories (MobLeLabs), a learning framework for smartphone-assisted experimentation. A short review of the functionalities of smartphones, a classification of these MobLeLabs, and ideas for physiology laboratory protocols are shared herein.

Rationale of MobLeLab

Mobile learning laboratories, or MobLeLabs, are learning objects developed for portable devices, such as smartphones and tablets, that work as mini-laboratories for hands-on activities (22). These learning objects are smartphone applications (apps) that must be operated by the user to collect physiolog-
patterns (13). Despite the rapid advance of computational technology, physiology education based on experimentation mostly remains physically restricted to the laboratories of educational institutions, which own and maintain the computers, interfaces, and plug-in sensors used in these practical lessons. In this sense, the concept of MobLeLabs frees the physiology instructor and the student from the obligation to be in the institution to perform experimental measurements in human physiology, since smartphones combine the features of sensors, an interface, and an analysis computer that are found in the laboratory, in a compact, accessible, and mobile format.

The origin and evolution of MobLeLabs follow the technological evolution of computer-assisted learning (CAL) and the natural fusion of laboratory equipment and computer software. In the 1970s, CAL, or computer-assisted instruction, was already present in science teaching as a didactic tool (14). The final path for the development of MobLeLabs was the advent of e-learning (electronic learning), which is a consequence of the development of CAL facilitated by the improvement of internet connections. E-learning was initially applied in educational institutions as a result of the increased accessibility to the internet by students, and it pertains to the learning processes developed on electronic platforms with no dependency on the time and space of the educational institution (28). Following the evolution of personal digital assistants, microcomputers, and telephones, m-learning (mobile learning) emerged as the best solution for learning at any time and place (21). Finally, the increase in the capacity of processing information and the memory of smartphones and tablets propelled the creation of MILOs (mobile interactive learning objects), which are applications/software designed to boost the interactivity during learning by means of portability, spontaneity, and personalization (17). Similarly, MobLeLabs thus emerged as MILOs designed for smartphone-assisted experimentation following the rapid development of new features of smartphones, tablets, and their high-quality sensors. Figure 1 summarizes the origin of MobLeLabs and illustrates how the experimental and education streams converged along with m-learning to lead to MobLeLabs. There are three types of MobLeLabs, depending on the manner that the data are collected: simulators, built-in, and plug-in.

**Classification of MobLeLabs**

To systematize the communication among educators and facilitate the retrieval of MobLeLabs for specific pedagogical purposes, we created a classification for the different types of MobLeLabs, depending on the manner through which the data are collected: simulators, built-in, and plug-in.

**Simulators.** This type of MobLeLab is a classical simulator that has been used worldwide in physiology courses but was developed for a mobile device platform. It allows experimentation because the system is programmed with algorithms based on physiological principles and laws. The learner does not type in raw data to be analyzed, but has to manipulate the variables to observe the final result. An example is the application (available only for iPad) Respiratory–Craytonium Interactive Physiology, designed by Craytonium Ltd. This application allows the students to change the values of variables to observe modulations in alveolar gas exchange, lung volume, cell gas exchange, and respiratory equations (Fig. 2, A–C).
**Built-in**. This is the most typical MobLeLab because the app per se is responsible for the collection and processing of the data. There are several sensors built in the structure of modern smartphones. These sensors allow the exploration of different variables of the physical world that can be used in physiology education activities. Depending on the features of the student’s smartphone, it can include a camera, microphone, GPS (global positioning system), proximity sensor, temperature sensor, humidity sensor, touch sensor, fingerprint sensor, pressure sensor, ambient light sensor, gyroscope, accelerometer, magnetometer, and image sensor (Fig. 3). The last four sensors are not very familiar to the majority of non-tech-savvy educators. They detect, respectively, angular rotational velocity and acceleration, linear acceleration, the Earth’s magnetic field, and information to integrate an image based on metal-oxide-semiconductor technology. An example of a built-in MobLeLab is the app Instant Heart Rate (available for Android and iOS) designed by Azumio to detect one’s pulse when users place the tip of their index finger on the camera lens. In this case, the smartphone detects the desired signal and generates a value from automatically coordinating the camera and the LED light of the device. Several types of heart rate apps, such as Instant Heart Rate, were validated and tested for reliability (8, 25), which provides more scientific accuracy for the creation of protocols for cardiovascular lessons (Fig. 2, G–H).

**Plug-in.** For the operation of this type of MobLeLab, an external device is required that contains a sensor to detect the variable. The external device is connected to the operational system of the smartphone or tablet through a cable to be plugged in or a Bluetooth connection. Obviously, the use of plug-in MobLeLabs for widespread remote education is limited due to financial restrictions and affordability. The app Mind Monitor (available for Android and iOS) was designed by James Clutterbuck and provides values and patterns for brain waves. However, it requires an electroencephalogram headband called MUSE, which contains sensors that record the electrical activity detected through the scalp of the user (34) (Fig. 2, G–H).

**Uses of MobLeLab in Physiology Education**

The use of MobLeLabs to promote learning physiology concepts is possible via the considerable number of variables of the human body that can be collected through noninvasive methods. Similarly, the advanced development of mobile applications for health monitoring should encourage educators to create, apply, and analyze protocols designed to teach physiology for grades K–12 and higher education students. The literature on MobLeLabs or smartphone-assisted experimentation for physiology education is still scarce. One example of the use of MobLeLabs for physiology education was presented by Nadal and Lellis-Santos (27), who described a protocol for exercise physiology education using genuine and alternative smartphone applications. Briefly, the volunteers engaged in a jogging protocol, housekeeping activity, or smartphone-guided meditation to evaluate their heart rate, respiratory rate, forced expiration, muscular tonus, and reaction time.

To demonstrate the applicability of MobLeLabs for remote physiology experimental learning, Table 1 summarizes these and other simple smartphone applications for experiments devised to illustrate each of the physiological systems around which most undergraduate courses are organized.

Clearly, Table 1 is not an exhaustive list of applications of MobLeLabs for human physiology teaching, but it is interesting to note that one can think of and find simple and useful alternatives to experimental and quantitative thinking for all major systems around which physiology courses are structured. However, the way in which MobLeLabs could be employed by students should be carefully considered by instructors when developing the protocols that guide them in MobLeLab use to guarantee learning effectiveness and safety, since the experiments will be conducted without on-site supervision. In this context, the search for validated applications is a sensible
recommendation to achieve more reliable data (8, 30). Some suggested smartphone applications are available in the Apple Store or Google Play, but others can be found only with the authorization of developers or the authors of the study.

**Elaboration of Protocols Using MobLeLabs**

The use of MobLeLabs can be stimulated through two learning methods: project-based learning or science class protocols. In both types of methods, some concerns must receive more attention, such as the ethics of experimentation, the standardization of the protocol and instructions, orientations and tools for data analysis, awareness of prank apps, and the accessibility of applications.

Before starting any smartphone-assisted experimentation using MobLeLabs, educators should discuss with faculty the ethical policies that are required by the educational institution. Some institutions do not allow educators to develop practical lessons without permission and approval by the institutional review board. Additionally, possible risks for human health associated with the experimental protocol should be either completely avoided or emphatically discussed with the students, especially if one is adopting a project-based learning methodology. We have observed and rejected the experimental approaches of students who planned to analyze variables after exposing themselves to unsafe conditions, such as marijuana use, alcohol use, intercourse activities, or exhaustive and extreme physical activities. For project-based learning, it is important that each project be reviewed either by the educator or through a guided peer-review activity.

To guarantee a reliable analysis of the experimentation, the protocol needs to provide scientific and precise guidelines. It is highly recommended to include drawings or videos in the protocols to illustrate the step-by-step orientations of the manipulation of the smartphone. For example, a protocol can include YouTube videos with instructions for dance movements to use MobLeLab to collect heart rate data (26). Several variables must be collected after specific movements (27), and any unforeseen misunderstanding of the instructions can create abnormal results. The identification of these outliers and the discussion of their possible causes can, however, be yet another opportunity for the instructor to promote learning by the students, particularly on the scientific method. Likewise, the collection of data for the control groups must be precisely described in the protocol. As such, we believe that the use of...
MobLeLabs as didactic tools is a fruitful opportunity to discuss scientific methodology and rigor in experimental biology. A strategy that we used was to ask high school students to devise hypotheses that could be tested through the use of an array of MobLeLabs and then submit their experimental design to fellow students so that they act as peer reviewers to judge whether the proposed experimental approach is sound. Since 2017, we have observed a myriad of hypotheses being tested by the students in their projects, such as testing the effect of caffeine on heart rate, the variability of balance before and after bedtime, and the impact of food consumption on sleep quality.

It is important to provide tables and charts to facilitate the organization of the data collected while also encouraging students to present their results in any type of data visualization. Experimentation for physiology education encompasses the analysis of values and quantitative methods, which can be quite confusing when performed during remote education. Educators can teach the students how to use statistics software and explain the importance of analyzing the dispersion of a variable rather than only using the final data.

Although some apps were purposely developed to operate as health monitors, the majority of them have not been validated. In these cases, the data collected will not be able to represent the precise value of the physiological variable of interest since its dimensions will be inferred by proxy from the actual parameter the app was devised to measure; however, it still can be used for educational activities with adequate disclosure. It is prudent for the instructor to verify the reliability and replicability of the measurements provided by an app by searching for studies that compare the app with conventional laboratory equipment. It is very important to advise the students of the existence of prank apps, which persuade the users with convincing graphical images and design but provide fake or random results for entertainment purposes. For example, some X-ray apps available in online stores induce users to think they are scanning body parts by matching the scan process with realistic radiographic images. Likewise, other so-called thermal camera apps promise to work without a connection to a thermal camera device, but they only provide image effects based on light intensity. The category in which the apps are classified in the store indicates the putative validity and reliability of MobLeLabs for physiology education. Applications in the medical, health, fitness, and education categories are likely to work better as MobLeLabs than apps classified as entertainment and games.

One limitation that the instructor should consider is the availability of apps for different operating systems, territories, and language barriers while developing MobLeLab-based protocols. Thus the instructor has to survey students to map their access to the desired app and search for solutions that accommodate all students. For instance, the app Neuro Physiology, developed by Craytonium Interactive Physiology, is only available for iOS (iPad only) in certain countries, but it can be replaced by the app The Nernst/Goldman equation simulator, developed by BioCommunications (available for iOS on the iPhone), or Action Potentials, developed by Nervi-AP (available for Android), as alternative apps for activities aiming to use MobLeLabs simulators. Moreover, some countries have restrictions on the availability of certain apps due to local policies. Furthermore, the majority of the apps are available only in English, which creates a barrier for non-English speakers. The dissemination of the use of MobLeLabs is likely to support actions to overcome these limitations and barriers.

Additionally, faculty should be aware of and guarantee that all the students have access to smartphones and stable internet connections at least to download the MobLeLabs to be used before implementing this strategy in their courses. This requirement could be met through a simple and anonymous survey sent to students via email and could be even more crucial in developing countries where, despite the huge expansion of access to mobile phones in remote and poor areas, which has been a factor of lower inequality, a social and gender digital divide still remains (32). Indeed, both students (41) and instructors (19) from developing countries express concerns regarding the overall effectiveness of m-learning strategies due to poor internet access.
### Table 1. Ideas of didactic protocols using MobLeLabs for physiology education

| Physiological System          | ID No. | Measured Variable                   | Type of MobLeLab        | Sensor                  | Suggested Experimental Approach                                                                 | Examples of Apps Available |
|-------------------------------|--------|-------------------------------------|-------------------------|-------------------------|--------------------------------------------------------------------------------------------------|----------------------------|
| Membrane physiology Nervous   | 1      | Membrane potential function         | Simulator               | None                    | Parameter variation (ion concentrations, membrane conductance, etc.)                            | Nernst/Goldman Equation Simulator |
|                               | 2      | Vestibular function                 | Built-in Gyroscope      |                         | In a rotating chair, with eyes closed, start angular speed recording and tap to stop recording when | SensorKinetics; Accelerometer (30) |
|                               | 3      | Saccadic movement                   | Built-in Camera         |                         | perception is of end of rotation                                                               | EyeTracker                 |
|                               | 4      | Sensory motor integration           | Built-in Touchscreen    |                         | In rotating chair, suddenly stop motion and try to track horizontally moving dot in screen app  | 2B-Alert App (31)          |
|                               | 5      | Neuronal physiology                | Simulator               | None                    | Measure time reaction with both dominant and nondominant hand, and in monocular vision either     | Neuro Physiology           |
|                               | 6      | Brain waves                         | Plug-in Electroencephalograph |               | with opened or closed eyes. Measure brain waves using MUSE headband                            | Mind Monitor (34)          |
|                               | 7      | Gait/balance                        | Built-in Accelerometer and gyroscope |               | Challenge the volunteer with conditions that disturb balance, such as blockage of visual cues or rotating movements. Measure gait | SmartMOVE (10)             |
|                               | 8      | Sleep/awake cycle                   | Built-in Accelerometer  |                         | Explore circadian cycle and phases of sleep                                                   | Sleep Time (4)             |
| Cardiovascular                | 9      | Heart rate                          | Built-in Camera and image sensor |               | Evaluation of heart rate and blood pulse before and after dynamic exercise or Valsalva maneuver or during motion | Instant Heart Rate (23); iPhysioMeter (24) |
|                               | 10     | Blood perfusion                     | Built-in Camera         |                         | Measure basal pulse; with a rubber band promote a minor blood flow occlusion and measure pulse; compare the waveforms | Instant Heart Rate          |
|                               | 11     | Cardiac electrophysiology           | Simulator None          |                         | Manipulate electrical variables that generate an ECG                                           | ECG Craytonium             |
| Respiratory                   | 12     | Respiratory function                | Simulator None          |                         | Manipulate variables of alveolar gas exchange, lung volumes, and cell gas exchange             | Respiratory Physiology     |
|                               | 13     | Forced expiration                   | Built-in Microphone     |                         | Submit the volunteer to a challenging condition and measure time during a single vowel expiration sustained over 50 dB | Sound Meter                |
| Digestive                     | 14     | Expiratory volumes                  | Built-in Microphone and mouthpiece |               | Submit the volunteer to a challenging condition and measure expiratory volumes                  | Wonkwang University Spirometer (38) |
|                               | 15     | Respiratory rate                    | Built-in Microphone and mouthpiece |               | Decrease in turbidity of starch suspensions due to saliva (1)                                  | Breath counter (19)        |
|                               | 16     | Starch digestion                    | Built-in Accelerometer  |                         | Decrease in turbidity of starch suspensions due to saliva (1)                                  | Light Meter (18); Color Assist Lite (43) |
| Urinary                       | 17     | Food intake × stool volume relationship | Built-in Camera        |                         | Weight amount of food taken and correlate with the area and color occupied by stool in pictures of toilet water surface in ensuing defecations | ColorAssist Lite           |
| Endocrine                     | 18     | Urine concentration/dilution        | Built-in Camera         |                         | Quantify yellow channel of pictures from urine samples before and after drinking 1 liter of water | ColorAssist Lite           |
|                               | 19     | Glycemia                            | Built-in and plug-in Camera and Uni-Clip test unit |               | Measure blood glucose after a meal or oral glucose tolerance test                                | PixoTest (20)              |
|                               | 20     | Cortisol                            | Built-in and plug-in Camera, image sensor, test strips |               | Measure circadian salivary cortisol                                                              | Smartphone Linked Stress Measurement (7) |
|                               | 21     | Cholesterol                         | Plug-in Electrochemical analyzer and test strips |               | Measure cholesterol after meal or explore cholesterol profiles                                  | Blood cholesterol monitoring (11) |
| Reproductive                  | 22     | Spermatozooid function              | Built-in and plug-in Camera, lightweight optical device, and microchip |               | Measure the concentration of motile sperm after ejaculation                                      | YO Sperm Test (44)         |
|                               | 23     | Ovulation cycle                     | Built-in Camera         |                         | Daily collect and spread vaginal sperm onto a thin glass surface and measure the light intensity crossed by sample from a same light source; correlate with temperature measurements | Light Meter (18) or Color Assist Lite |

### Conclusions

Considering the possible applications that were briefly described herein, MobLeLabs seem to be a feasible reality for off-campus teaching and learning, particularly for human physiology, as students tend to see computer-assisted electronic learning as beneficial in terms of time flexibility (35), which seems to be particularly relevant in situations with emergency remote teaching, as during the current COVID-19 pandemic.
While this form of emergency education must not be con-
ounded with regular online or distance learning (15), MobLe-
Labs could be a reliable strategy to maintain some sort of
practical teaching in social isolation. In addition, MobLeLabs
might also be useful during the return of on-campus activities
to optimize/adjust time for both students and instructors when
catching up on the learning objectives that may have lagged
behind during this period. The use of MobLeLabs represents a
creative solution for educational institutions that have limited
or no financial support to purchase laboratory equipment. Even
when the pandemic is over, we believe that MobLeLabs should
have a growing presence in the repertoire of physiology teach-
ing approaches.

DISCLOSURES
No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS
C.L.-S. and F.A. conceived and designed research; C.L.-S. and F.A. analyzed data; C.L.-S. and F.A. interpreted results of experiments; C.L.-S. and F.A. prepared figures; C.L.-S. and F.A. drafted manuscript; C.L.-S. and F.A. edited and revised manuscript; C.L.-S. and F.A. approved final version of manuscript.

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