Innovations

Plant Tracer: A Program to Track and Quantify Plant Movement from Cellphone Captured Time-Lapse Movies

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Abstract Despite the fundamental importance of plants to our very survival, student interest in plant biology is in decline as technology draws us further away from nature. Here we introduce *Plant Tracer* (http://www.planttracer.com), a Matlab-based program, which can quantify time-lapse videos of plant movement. We demonstrate that Plant Tracer can be used to distinguish altered movement qualities in the inflorescence (flowering) stem in the Arabidopsis *pgm-1* (phosphoglucomutase) mutant when compared to wildtype, providing a genetic platform for students to evaluate how plants sense and respond to gravity and circumnutation (the back-and-forth swaying of plant organs). We show that both gravitropism and circumnutation is diminished in the *pgm-1* mutant when compared to wildtype. In this way, *Plant Tracer* is a promising instructional tool for biology labs to quantify the genetics of plant movement using smartphones.

Keywords plant biology, plant movement, *Plant Tracer*, software, movement quantification, movement tracking, gravitropism, circumnutation, *Arabidopsis thaliana*

Introduction

Time-lapse photography has proven itself to be a promising instructional tool in biology lectures to stimulate interest in plants, enabling student visualization of the complexities of plant development and movement (Fitzgerald, 2012; Hangarter, 2000; Harrison-Pitaniello, 2013; Stark, 2008). Building upon this technology, a plant time-lapse photography educational lab was created where students use their personal digital devices to record and visualize movement in the flowering stems of the genetic model plant, *Arabidopsis thaliana* (Brenner, 2017). *Arabidopsis thaliana* exhibits rapid positional changes in the inflorescence in a little more than an hour (Brenner, 2017; Niinuma, 2005; Masson, 2002). This active learning lab not only increased student interest in plants but also inspired nearly half of the students to share their smart phone derived videos with friends and family (Brenner, 2017), effectively amplifying the educational impact of this approach.

While this method of having students create plant movement time-lapse movies was successful at increasing engagement, it yielded only qualitative, not quantitative data, hence, the development of software that not only tracks, but also analyzes plant movement is the logical next step for students to directly become active in the field of plant-movement research. Developing this method is especially useful in that currently available plant movement-tracking software is targeted exclusively to academic research laboratories, thus necessitating the use of expensive cameras, and requiring knowledge of computer coding languages (Stolarz, 2014; Wagner, 2017; Greenham, 2015). In addition, most existing plant movement tracking software is merely limited to examining only one type of movement, one organ, or one species of plant. Here we introduce a Matlab-based (MATLAB, 2015b) graphical user interface (GUI) software program, *Plant Tracer*, to not only bring the dynamism of the plant into the classroom, but also to provide investigators with tools to analyze this

movement and gather quantifiable data to better understand plant movements.

Among the fascinating and sophisticated movements that plants make are tropisms (movement towards or away from a stimulus), and nutations (back and forth movements that occur with no obvious stimulus). Time-lapse technology can capture these movements to stimulate student engagement by revealing this dynamism (Brenner, 2017; Fitzgerald, 2012; Harrison-Pitaniello, 2013; Hayden et al. 2011). Gravitropism, the re-orientation of plant organs in response to gravity has been well documented by Charles Darwin (Darwin, 1865). Darwin hypothesized in 1903 that the mechanism of gravitropism is activated by the settling of mobile starch-synthesizing organelles called statoliths in root tissue in response to gravity, and this hypothesis was further augmented by Zimmerman in 1924. Statoliths are easily stained and observed in the classroom, where they are found in the gravity sensing columella cells of the root cap (Kiss, 2000). It is still not known exactly how statoliths initiate the gravitropic cascade, but it is theorized that statoliths activate mechanosensitive pathways in the actin cytoskeleton that subsequently cause the asymmetric distribution of the major regulatory plant hormone auxin, causing a response in the stem to bend in reorientation against gravity (Chen, 1999; Blancaflor, 2003; Band, 2012; Wyatt, 2013). One strong piece of evidence that statoliths function as the, or one of the gravity vector sensor(s), comes from the Arabidopsis mutant, phosphoglucomutase-1 (*pgm*) (Vitha, 2000; Weise, 1999). This mutant is blocked in a key step involved in starch formation, and thereby consequently deprived of statoliths (Weise, 1999). As a way of easily demonstrating the role of statoliths in shoot gravitropism, students can easily observe—during a single class laboratory—impaired shoot reorientation in *pgm-1* compared to wildtype (Kiss 2000).

Circumnutation is another type of plant movement. It is a complex and poorly understood process that is universal to all plants (Darwin, 1880; Stolarz, 2009). Circumnutation is the back-and-forth swaying found in plant organs (Darwin, 1880; Stolarz, 2009), but little is understood about why and how it occurs. Like all nutations, circumnutation is influenced, but also exists independently of external stimuli (Stolarz, 2009; Schuster, 2010). Circumnutation is influenced by the circadian clock, light, temperature, chemicals, organ morphology, and age (Stolarz, 2009; Schuster, 2010; Niinuma, 2005; Kitazawa, 2005). Circumnutation has been shown to be influenced by gravisensing cells, auxin, ion channels, and proton pumps but its mechanism and purpose is not well understood (Stolarz, 2009; Schuster, 2010; Niinuma, 2005; Kitazawa, 2005). To engage student interest in plants, circumnutation is a highly dynamic and intriguing process where one nutation (back and forth motion) can be observed within one lab period using the model genetic plant *Arabidopsis thaliana* (Brenner, 2017).

With *Plant Tracer* students first create plant movement footage using the application Lapse It (http://www.lapseit.com) as described in Brenner, 2017 and then upload these time-lapse movies into *Plant Tracer* (which currently runs as an executable Matlab-originated (MATLAB, 2015b) program available for download), in order to quantify movement rate, and periodicity (distance moved) during gravitropism or circumnutation. *Plant Tracer* enables students to not only quantify changes in plant movement, but also compare movement values between different strains, mutants, and other plant variations for scientific discovery. Here we use *Plant Tracer* to demonstrate reduced movement qualities in the *Arabidopsis thaliana* mutant, *pgm-1*, when compared to wildtype.

Methods

Plant Tracer Software Development

Plant Tracer was developed in Matlab (MATLAB, 2015b) and functions as an executable program, allowing it to be downloaded without charge and to be run independently of the base program. *Plant Tracer* is installed on a personal computer running either Mac OS or Windows operating systems.

To track *Arabidopsis thaliana* apex movement, we modified the basic block matching algorithm to detect a moving inflorescence stem apex (Fig. 1) (Lu & Liou, 1997). This algorithm is used as a method of locating matching blocks in a sequence of digital video frames for the purposes of motion estimation. The underlying assumption behind this method is that the visual pattern of a block enclosing the apex stays approximately the same from frame to frame. In *Plant Tracer*, starting with a manually annotated block in an initial frame, its position in the current frame is determined by an exhaustive search, which calculates a matching cost function between the block in the previous frame and each candidate block in the current frame centered at each possible location in a search window. The candidate block with the least cost is then chosen for the current frame, and the process continues to the next frame.

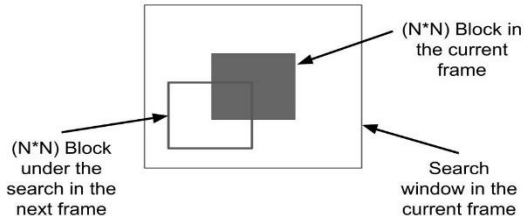

Figure. 1. Mechanism of Block-matching Algorithm.

$$Cost\ Function = \frac{1}{N^2}\sum_{i=0}^{N-1}\sum_{j=0}^{N-1}\left|F_{ij} - C_{ij}\right| + W_2\|\mathbf{x}_F - \mathbf{x}_C\|_2 + W_3\|(\mathbf{x}_F - \mathbf{x}_C) - (\mathbf{x}_C - \mathbf{x}_P)\|_2 ,$$

Figure. 2. Cost Function Equation.

Block matching is based on minimizing a cost function (Fig. 2). In *Plant Tracer*, we have modified the cost function of the basic block-matching algorithm to incorporate constraints on possible apex movements.

The cost function equation is shown where N is block width (which is assumed to be the same as block height), F_{ij} and C_{ij} are the luminance intensity values of pixels in the current and previous blocks, respectively. x_F, x_C and x_P are the block center coordinate vector in the current frame, the previous frame, and the previous frame before that, respectively. W2 and W3 are weighting parameters. The first term is the mean absolute difference (MAD) which calculates the intensity difference between two connected frames. The second term represents the distance the apex traveled between two frames. The third term is the difference magnitude of the apex movement in two successive inter-frame periods. Note that 2 indicates the L2 norm or length of a vector. By adding the second and third terms, we favor candidate blocks that undergo small and smooth motion from the previously determined blocks, among those that have similar MAD as the previous block. Through empirical trial and error with our testing videos, we set W_2 and W_3 to 0.375 and 0.175, respectively.

To alleviate the influence of any pattern(s) on the background on continuous tracking, we apply background subtraction prior to the block matching algorithm. Here we assume the background is stationary and obtain the background image for a frame by averaging the past 10 frames. Then, we subtract the background image from the current frame and threshold the difference image. For each pixel, if the absolute value of the difference is smaller than a threshold value, this pixel is set to 0 in the current frame. Otherwise, the original value is kept. We then apply the block matching algorithm on this background-removed frame. A threshold value of 20 is found to work well (the intensity range is from 0 to 255).

Plant Culture Methods

Standard Arabidopsis cultivation methods were performed as described according to Brenner (2017). Seeds from the *Arabidopsis thaliana* genotype Columbia (Col) as the control, and the mutant phosphoglucomutase (*pgm-1*) (which can be ordered as a "teaching kit" through the Ohio Biological Resource Center (#CS19985)) were cultivated in 2 ½ inch (side) square plastic pots containing MetroMix 360 (Sun Grow) soil or on hydrated jiffy-7 soil pellets (Carolina Biologicals). Water was applied to the tray under the flat holding the plants so that water seeped into the soil from below. In both cases plants were fertilized with water containing Miracle Grow Bloom Booster Flower Food fertilizer powder [NPK of 15-30-15, with the following microelements: B (0.02%), Cu (0.07%), Fe (0.15%), Mn (0.05%), Mo (0.0005%), and Zn (0.06%)]) at day 10 after the seeds were sown. Plants were cultivated for approximately 4-6 weeks under fluorescent lights on growth carts. Light conditions consisted of 16 hours of light and 8 hours of dark.

Staging a Time Lapse Recording

Recordings were made using a standard portable electronic device such as a tablet or smartphone. The developmental stage used for this analysis is reached when the inflorescence stem is approximately 2-6 cm tall. At this stage the first flowers are just beginning to undergo anthesis (flowering opening). It is important to choose plants with only a small number of inflorescence shoots, or ideally a single shoot. If a plant with more than one shoot is tested for gravitropism, it is important to avoid situating the plant, so that one shoot might move across the path of another shoot, leaf, or other structure, which may cause the tracking algorithm to lose track of the subject.

During testing of either circumnutation or gravitropism digital recordings were made with Arabidopsis strain Columbia, as a control vs. the *pgm-1* mutant, as shown in Fig. 3. Key materials for the imaging set-up include a solid black background (shown here as a black office folder), a metric ruler (with white lettering and white increments set on a black background for best contrast). The ruler is used to calibrate the true distance within the movie. Labels are placed in close proximity to the plants so that the identity of the plant strain/genotype can be clearly seen in the recording.

An experiment designed to measure the movement parameters of gravitropism is initiated by tipping the *Arabidopsis* plant 90 degrees to position it on its side (Fig. 3); whereas, an experiment to measure circumnutation is set up by simply leaving the plants in their original upright orientation as shown in Fig. 3. For both gravitropism and circumnutation the ruler must be placed in the same focal plane as the apices so as to not distort the measured values.

Making Time-Lapse Videos with Lapse-It

Lapse It is a free, simple, and publicly-available time-lapse App compatible with Android and iOS

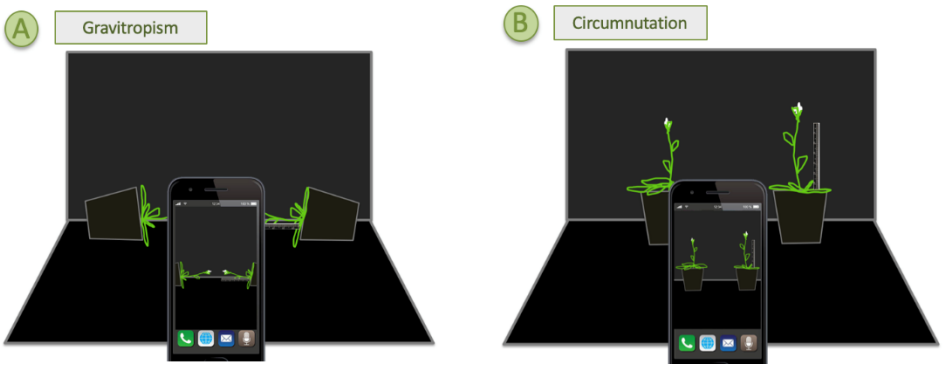

Figure 3. Experimental Staging of Time-lapse Recording

devices (http://www.lapseit.com). To create a time-lapse recording of Arabidopsis, in the Laspe-It settings page, the "Capture Interval" is set to capture an image once every two minutes and the render settings are set for 20 "Frames per Second". Gravitropic analysis in Arabidopsis is typically complete after at least 1 hour and 30 minutes but can be run longer if desired. Circumnutation studies run for at least three hours minimum (the approximate time for one full nutation) but can be continued for 1-3 days (or until the apex has moved out of camera frame). Upon completion of the movie, the video should be "rendered" in Lapse-It and then saved to the device's camera roll. The video should then be transferred to a computer for analysis using *Plant Tracer*.

Downloading and Installing *Plant Tracer*

An "executable" version of *Plant Tracer* can be downloaded at http://www.planttracer.com; *Plant Tracer* is compatible with both Mac and Windows operating systems. To download click on the Matlab icon on the website front page as shown in Fig. 4. In the downloads folder, double click on the 'PlantTracer1.0-mac.zip' or 'PlantTracer1.0-windows.zip' file to decompress the file. Then in the downloads folder, right click on MyAppInstaller and select open from the menu to begin installation. The program installer will pop-up, and you can navigate through the installer to complete installation. Once installed, navigate to the Applications folder the folder titled '*PlantTracer*'. In *PlantTracer* > application > one can find the PlantTracer program. Right click and select open to access the interface.

Using *Plant Tracer*

Before use it is helpful to view this tutorial video, showing how to utilize *Plant Tracer* for either circumnutation https://www.youtube.com/watch?v=VN2cBPuqBzk, or for gravitropism https://www.youtube.com/watch?v=evsTLrZacwE tracking.

The steps to use *Plant Tracer* for video analysis are also shown in Fig. 5. Analysis is initiated by

Figure. 4 The *Plant Tracer* Website. Arrow refers to Matlab icon. Click icon to initiate download of *Plant Tracer* program.

clicking on the folder (Icon 1) to upload a rendered Lapse-It video into *Plant Tracer*. Upon upload, the first frame of the video is shown in the viewer. There is a panel to the right of the viewer, where one enters information necessary for quantification. The first step is to trim the movie to the region of interest by using the slider bars at the bottom of the interface (Icon 2). If the software Lapse It was used to create the time-lapse movie, be certain to trim off the Lapse it logo that appears at the end of the movie. To do this, use the right slider to trim the logo (Icon 2).

Next, before 'tracing' plant movement, two parameters are inputted into *Plant Tracer*. First, the capture interval used to make the video is entered into the box beside "Capture interval" (Icon 3). The Capture interval is found in settings in Lapse It as pictures taken per minute (the default value of 0.5 [one picture is taken every two minutes] works well for recordings of Arabidopsis inflorescence stem movement). The second value to enter is the internal distance calibration. To do this, check the box beside "Set scale" (Icon 4). This will then prompt the user to click on two points in the video frame along the margin of the ruler to draw a straight line ("that spans a known distance"). After the line appears spanning the two clicked points, next right click or hit 'enter' on the keyboard to exit the line drawing mode. Next enter the value (in mm) of the length of the line drawn into the data entry box for "Set scale" (Icon 4). Next under the

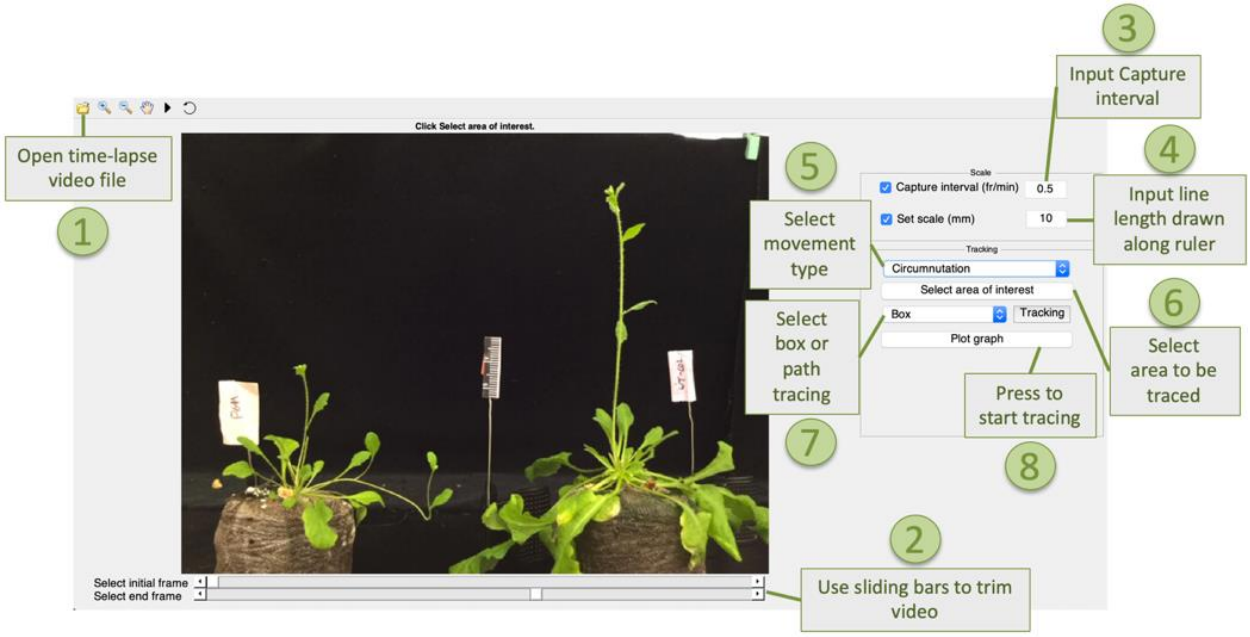

Figure. 5 The *Plant Tracer* Interface. Boxed text and lines in green point out action steps in the *Plant Tracer* interface to analyze a time-lapse movie of plant movement. Tasks should be completed in consecutive order from Icon 1 - Icon 8. See the video Circumnutation Tutorial at https://www.youtube.com/watch?v=VN2cBPuqBzk or Gravitropism Tutorial at https://www.youtube.com/watch?v=evsTLrZacwE for a descriptive walk through of the *Plant Tracer* program.

heading "Tracking" the user selects the plant movement behavior of interest, either circumnutation or gravitropism (Icon 5). Next, click on "Select Area of Interest" (Icon 6), which enables the user to draw a tracking rectangle on an organ, or segment of an organ to 'trace'. Next, the user chooses either "Select box or path tracing" (Icon 7) to generate either a box or a tracing line that will follow the path of movement. Once the area of interest and movement type has been chosen, "Press to start tracing" (Icon 8) is clicked and *Plant Tracer* will automatically run the block matching algorithm. While the computer is tracking the moving plant the program follows the path of the "gravitroping" or circumnutating selected object. By clicking on "Plot graph" the data output will create a graph revealing the x (horizontal) and y (vertical) components along a Cartesian (x,y) grid system of the positional changes of the object as shown in Fig. 6 A, B. For gravitropism, the vertical direction is chosen to measure the ascendance of the flowering stem apex.

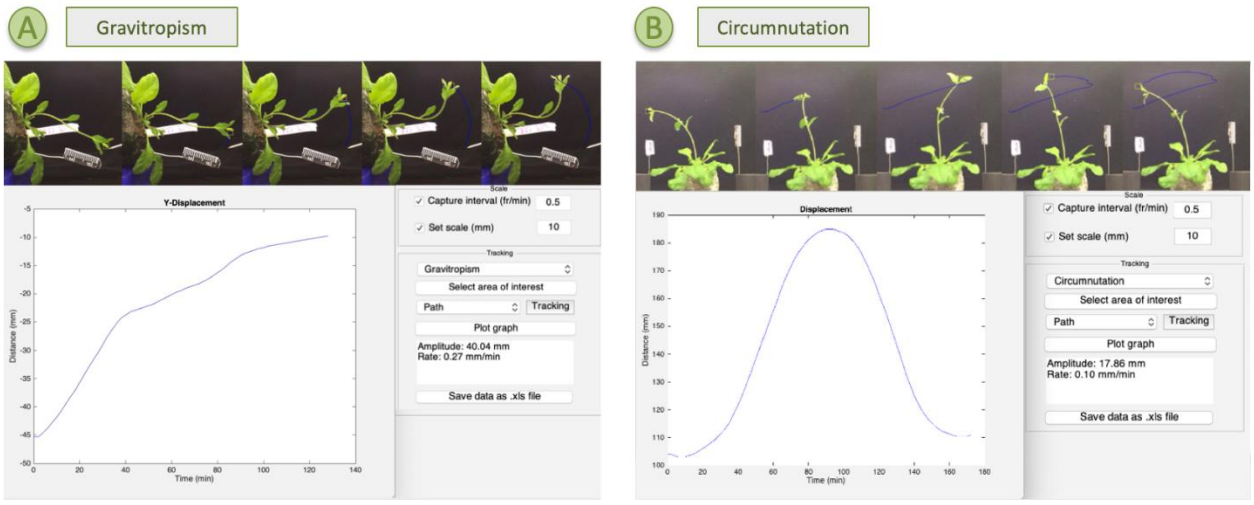

Figure. 6 Still shots reveal progression of plant movement during *Plant Tracer* analysis of gravitropism and circumnutation from *Arabidopsis thaliana* wildtype genotype, Columbia. Still shots demonstrate progression of movement coupled with an x,y output plot alongside the program interface. Movement calculations include amplitude and rate for A. vertical displacement during a gravitropism. B. horizontal displacement during circumnutation.

For circumnutation, the horizontal direction is chosen to measure the periodic back-and-forth swaying of the flowering stem apex. The output plot values are reported in the *Plant Tracer* including amplitude (mm) and movement rate (mm/min) flowering shoot apex (Fig. 6 A, B).

Results

Plant Tracer as a tool to measure plant movement

Plant Tracer is designed to measure plant movement from time-lapse recordings. In order to test the accuracy of *Plant tracer*, the actual distance an Arabidopsis apex moved was hand measured and compared to the software's calculated output. Whilst there are concerns about the 3-D movement of the plant being reduced to two dimensions, analyses of hand-measured vs Plant-Tracer computed amplitudes and rates of movement show no significant difference (Fig. 7).

We tested *Plant Tracer* to determine if it could detect impaired movement qualities in an *Arabidopsis thaliana* line that is deficient in gravitropism, the starch mutant line phosphoglucomutase, *pgm-1*, during both gravitropism and circumnutation in comparison to wildtype, Columbia. *pgm-1* has been previously reported to exhibit a slower gravitropic response in both movement rate and change in angle due to a perturbation of the starch-dependent gravisensing mechanism (17). In a pairwise comparison of 16 control Columbia plants compared to 16 *pgm-1* mutant plants, all mutant plants were shown to have significantly smaller amplitude of movement and a lower movement rate during gravitropic response (Fig. 8). Furthermore, *pgm-1* mutants showed a decrease in circumnutation rate and amplitude of horizontal movement (Fig. 8).

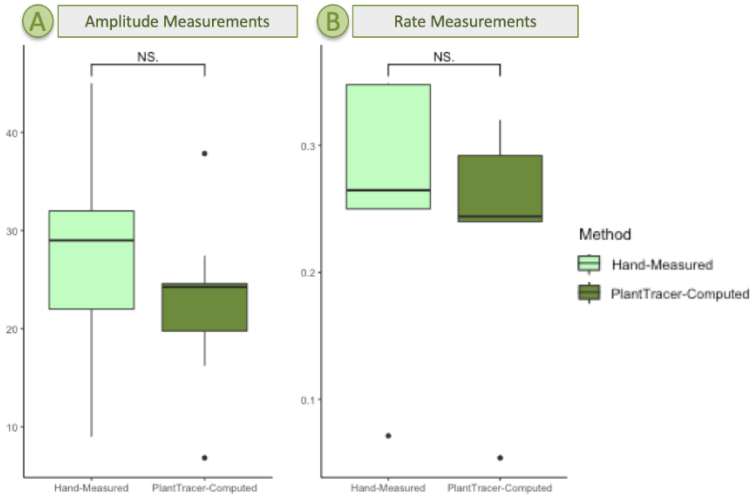

Fig. 7 Testing the accuracy of *Plant Tracer*. Comparative boxplots of hand-measured and *Plant Tracer*-computed amplitude measurements. Rate measurements are not significantly different.

Discussion

Time-lapse photography is an excellent way to discern and analyze plant movement and can encourage student interest in plant biology. It brings the plant world --that to many is often seen as static-- into the relatable dynamic present. Bringing the dynamism of plants to life makes plants more relatable and interesting to students. Along with this the *Plant Tracer* software also enables them to analyze the data from their videos to characterize this process.

While we have begun to use this software to look at circumnutation and gravitropism in a handful of Arabidopsis mutant lines, we envision the flexibility of the program to potentially measure other movement properties in Arabidopsis and movement in other plant species in future iterations. We have chosen Arabidopsis because it has fast growth and movement, when compared to other easily grown species and also because it has tremendously rich genetic resources which would enable the further identification of genes that may be involved in movement processes (23). In addition, Arabidopsis is easily grown indoors and is highly suited for classroom studies (10, 23). Currently we are working to create a version of *Plant Tracer* that will operate independently on the smartphone, which we believe will dramatically increase userability among students (a beta test version of App can be download from www.planttracer.com). The development of *Plant Tracer* in Matlab is the first step

towards our ultimate goal of constructing a hand-held App. Through the use of *Plant Tracer* we aim to expose these dynamic processes to a wider audience, as well as give students the opportunity to easily perform novel experiments and make original discoveries in the field of plant movement.

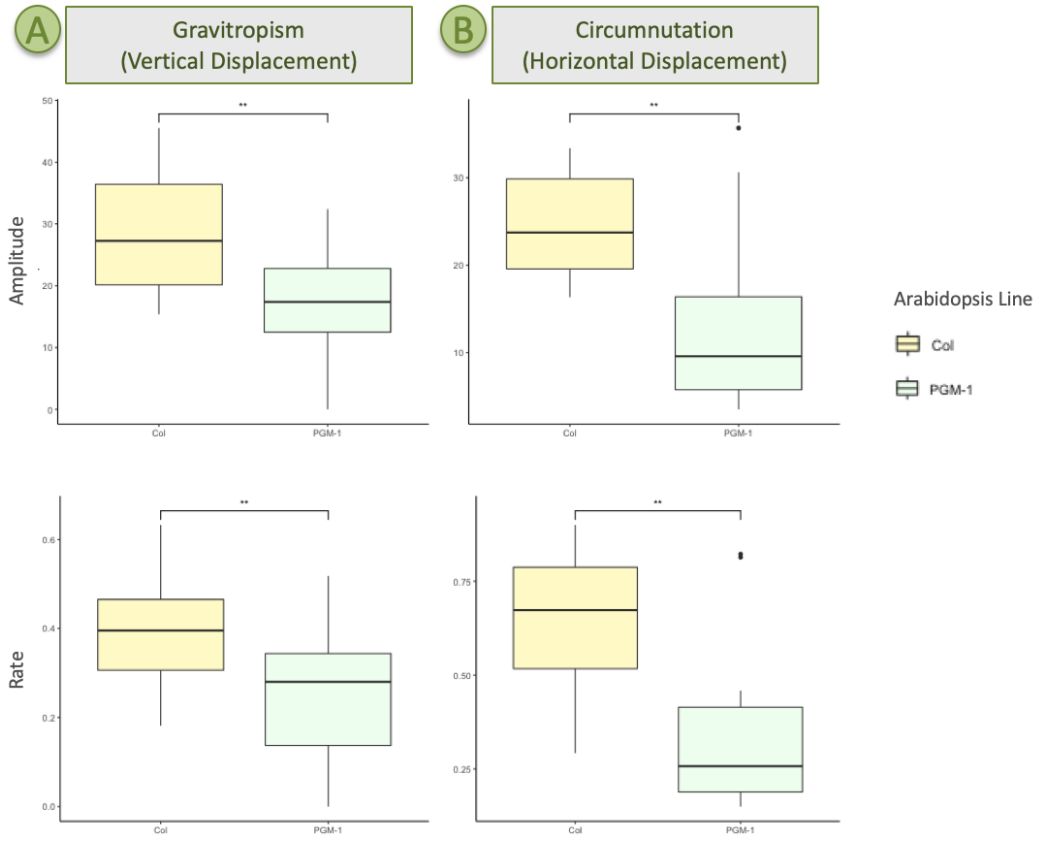

Fig. 8 Comparative analyses between *pgm-1* vs. Wildtype Columbia Arabidopsis lines. Boxplots show median value differences and 1st to 4th quartile differences between medians Columbia (yellow) vs. *pgm-1* starch mutant (green) lines after repeated tests (n=16, n=16). Asterisks indicate a significant difference in median values obtained via Student's t-test. One asterisk indicates $p<0.05$, two $p<0.005$, and three $p<0.0005$ A. Amplitude and rate of vertical displacement (gravitropism) B. Amplitude and rate of horizontal displacement (circumnutation).

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