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A comparison between battery-powered and human-powered ascents by a climbing arborist

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ABSTRACT

Climbing arborists often use a throwline and weight to set a climbing line in a primary support point (PSP) from the ground, which improves efficiency but can increase risk because the climbing arborist cannot carefully inspect the PSP. Efficiency may be further improved if the climbing arborist ascends using a powered device, but few studies have investigated their performance. The author measured loads at and inclination of fifteen PSPs as he ascended by hand or by a battery-powered device. We also measured the climbing arborist's heartrate and ascent duration. When the climbing arborist ascended by hand, loads were similar to when he used the powered device, even though the device increased the weight of the climbing system. Normalized by load, inclination at and below the PSP was also similar between the two ascent techniques; it was also related to both the distance of PSP from the main stem and PSP diameter, as expected from beam theory. The powered device reduced ascent duration by 56% and the climbing arborist's heartrate was also less than when he ascended by hand. The powered device conferred advantages in efficiency without increasing the likelihood of PSP failure. Climbing arborists should be careful to inspect the PSP and the stem below it for load-bearing capacity.

1. Introduction

Climbing arborists often set a climbing line in a tree from the ground; the use of throwlines has made it easier to set the line in or near the primary support point (PSP) from the ground. Doing so improves efficiency because the climbing arborist does not need to repeatedly retie their climbing line at successively higher locations until reaching the PSP. Selecting such a PSP in the center and near the top of the crown allows a climbing arborist to move safely and efficiently through the tree crown (Lilly & Julius, 2020). One risk with setting the climbing line near the top of the crown from the ground is that the climbing arborist cannot carefully inspect the PSP or the stem below it to assess its load-bearing capacity, which depends on stem diameter, wood strength, and the presence of defects such as decay or included bark.

To reduce the likelihood of PSP failure, arboricultural safety standards from countries around the world sometimes include guidance for selecting and pre-testing a PSP before an ascent. In the United States, §8.1.11 of the industry safety standard (Z133, ANSI, 2017) instructs climbing arborists to assess the load-bearing capacity of a prospective PSP by loading it to a magnitude twice the anticipated loads during arboricultural operations. But falls from height continue to represent about one-third of fatal occupational injuries to tree workers (Wiatrowski, 2005; Buckley et al., 2008; Castillo and Menéndez, 2009). Ball et al. (2020) found that about one-third of 56 fatal and non-fatal injuries involved PSP failures during ascents.

The likelihood of PSP failure depends on its load-bearing capacity as well as the loads it must bear as a climbing arborist ascends into, works in, and descends from the tree (Cetrangolo et al., 2018). Several previous studies have quantified the magnitude and frequency of loads associated with ascent techniques (Kane, 2018; Kane et al., 2020), anchor setups (Kane, 2020b), climbing lines (Kane & Arwade, In Press), presence of leaves (Kane et al., 2020), work actions (Kane, 2021), sudden stops during descents (Kane, 2020a), and simulated falls (Kane, 2020a). Few studies have quantified the movement of a PSP in response to applied loads as a surrogate for load-bearing capacity (Kane, 2021).

Arboricultural tree climbing is also physically demanding, requiring muscular and cardiovascular fitness. The trade literature often refers to arborists as industrial athletes (Carpenter and Skiera, 2013). Powered ascending devices are a recent introduction to the tools used by climbing arborists, marketed as an energy-saving device to quickly lift a climbing arborist into a tree. Reviews of powered ascending devices appear to be limited mostly to informal, online discussions among practitioners, although Shepard (2020) briefly reviewed the Ronin Lift (Ronin Revolution, Placentia, Calif., USA) in a trade magazine; the author did not

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present performance data, however. There do not appear to be any peer-reviewed studies that have investigated the use of powered ascenders in arboriculture.

The study had two objectives:

1. To quantify the following variables: (i) loads experienced by and movement of a PSP, (ii) a climbing arborist's heartrate, and (iii) ascent duration, as a climbing arborist ascended to a PSP using two different ascent techniques—by hand and using a powered ascending device;
2. To investigate the effect of PSP geometry on the amplitude of its movement as a climbing arborist ascended with two techniques.

2. Methods

2.1. Trees

In August 2021, when trees were in leaf and daytime high temperatures averaged 30° Celsius, we conducted trials on five *Quercus rubra* L. growing in a residential yard in Sunderland, Mass., USA (USDA Hardiness Zone 5a). Each tree included a large primary branch with nearly vertical orientation; the primary branch also had at least three lateral branches, each of which was large enough to serve as a primary support point (PSP). We selected three PSPs on the primary branch in each tree to include a range of diameters and horizontal distances from the trunk (Fig. 1). Selecting PSPs in this way allowed us to investigate the effects of diameter and leverage on movement of the PSP as a climbing arborist ascended or remained stationary using two ascent techniques (described below). Table 1 includes trunk diameter 1.4 m above ground and the location and size of three primary support points (PSPs) located on a single primary branch in each tree. Measured axially along the primary branch and horizontally from the main trunk, PSP 1 was the farthest and PSP 3 was the closest.

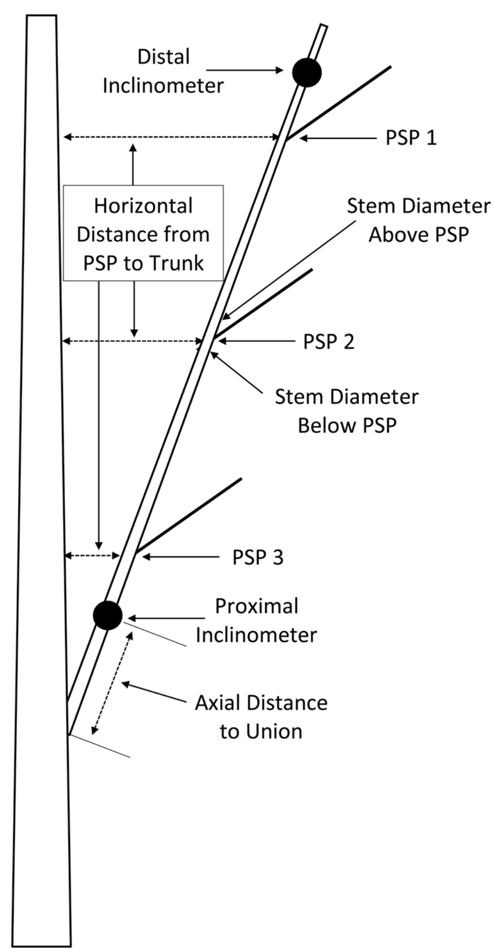

Fig. 1. Diagram (not to scale) of a primary branch showing three primary support points (PSP), two inclinometers (filled circles), and measurements listed in Table 1.

2.2. Setup

To measure movement of the primary branch that supported three PSPs in each tree, we installed two biaxial inclinometers (G-Link, Lord Microstrain, Williston, Vt., USA) to measure inclination (°) at 8 Hz at two locations on the primary branch (Fig. 1). We measured inclination to assess branch motion associated with the ascent techniques and climbing actions described below. Branch motion reflects the magnitude of bending stress, which influences the likelihood of failure. Table 1 includes the location of each inclinometer relative to each PSP and the primary branch union with the main trunk. Below, we refer to inclinometers as "distal" (farther along the primary branch than the distal PSP) and "proximal" (closer to the primary branch union than the distal PSP). The diameter of the primary branch at the proximal inclinometer was always greater than the diameter at the distal inclinometer (Fig. 1). Similarly, the horizontal distance between the proximal inclinometer and the attachment of the primary branch to the trunk was always less

Table 1
Trunk diameter 1.4 m above ground (DBH), angle from vertical of the stem with three primary support points (PSPs), and location and diameter(s) of the PSPs and two inclinometers in five *Quercus rubra*; all diameters are in cm and all distances are in m. Fig. 1 illustrates the locations and diameters.

	Tree	1	2	3	4	5
	DBH	44	56	41	44	43
	Stem Angle	15	21	4	13	16
PSP 1	Stem Diameter Above	8.1	8.9	7.6	10.4	11.2
	Stem Diameter Below	10.4	8.9	9.4	11.7	11.2
	Branch Diameter	7.6	5.6	4.8	6.1	6.4
	Height	21.0	20.6	22.2	19.4	20.5
	Horizontal Distance from Stem	1.7	1.0	0.7	1.1	1.9
	Axial Distance to Branch Union	7.2	2.5	5.9	5.3	6.8
PSP 2	Stem Diameter Above	11.4	10.4	10.7	13.0	10.9
	Stem Diameter Below	12.2	11.4	15.0	15.5	11.9
	Branch Diameter	8.9	5.6	15.5	8.9	6.4
	Height	18.9	19.9	20.4	16.8	19.7
	Horizontal Distance from Stem	1.0	0.7	0.5	0.5	1.7
	Axial Distance to Branch Union	5.0	1.6	4.3	2.8	6.0
PSP 3	Stem Diameter Above	13.0	11.7	14.2	16.0	15.2
	Stem Diameter Below	13.2	13.0	16.5	10.4	18.8
	Branch Diameter	17.5	10.9	9.4	18.8	10.9
	Height	17.7	19.8	19.4	15.1	17.1
	Horizontal Distance from Stem	0.8	0.4	0.5	0.1	0.9
	Axial Distance to Union	2.9	1.3	3.4	1.5	3.3
Distal Inclinometer	Stem Diameter	8.1	8.9	7.6	10.4	8.1
	Height	21.1	20.8	22.3	19.6	20.8
	Axial Distance to Branch Union	7.3	2.7	6.1	5.5	7.1
Proximal Inclinometer	Stem Diameter	11.2	14.0	17.3	15.0	15.0
	Height	19.3	18.5	19.0	15.6	18.1
	Axial Distance to Branch Union	2.6	0.6	2.9	2.0	4.4

than the horizontal distance between the distal inclinometer and the attachment of the primary branch to the trunk (Fig. 1).

We set a webbing sling in a basket hitch around one of the three PSPs in a tree and used a shackle to connect it to an Impact Block (StraightPoint LLC, Camarillo, Calif., USA), which measured loads at 8 Hz. We passed a climbing line (Scion, 11.7 mm diameter, Sterling Rope, Biddeford, Me., USA) around the sheave of the Impact Block and set up a basal-anchored stationary rope system (Lilly and Julius, 2021). anchored one end to the base of the tree using a single path, eye-and-eye polyester rigging sling (I&I Sling, Norwood, Mass., USA) in a choker hitch. The other end of the climbing line hung vertically from the Impact Block A single climbing arborist who performed all trials ascended on the free end of the climbing line—this configuration is known as a basal-anchored stationary rope system (SRS) (Lilly and Julius, 2021). The angle between the two parts of the climbing line changed between PSPs because PSP 3 was lower and horizontally closer to the trunk than PSP 2, which, in turn, was lower and horizontally closer to the trunk than PSP 1 (Fig. 1). The change in the angle was less than five degrees, which was too small to influence the resultant load measured at each PSP.

2.3. Trials

We only conducted trials when ambient wind speed was less than 2 m/s and on days without precipitation. At the beginning of the day, the climbing arborist attached an optical sensor (Verity Sense, Polar Electro Inc., Bethpage, N.Y., USA) to his left arm. The sensor measured heartrate (HR) at 1 Hz in beats per minute (bpm). The climbing arborist's resting heartrate (RHR) was measured during the hour(s) before beginning trials. He also weighed himself with his climbing gear. After installing the distal and proximal inclinometers on the primary branch, the climbing arborist randomly selected which PSP (1, 2, or 3) to conduct the first trials on. He set up the basal-anchored SRS on the PSP and conducted two trials each ascending by two different techniques (four trials total) in random order. He rested between trials until his HR returned to his RHR. After completing four trials on the first PSP, he randomly selected one of the remaining two PSPs to conduct another two trials of each ascent technique, followed by four trials on the last PSP in the tree. On each day, he completed twelve trials in total.

Ascent techniques included (i) ropewalking, which we refer to below as "ascending by hand"; and (ii) using a battery-powered ascending device (Lift, Ronin Revolution Corp., Placentia, Calif., USA). The Lift weighed 104 N. For ropewalking, a standard ascent technique for SRS (Lilly and Julius, 2021) with which the climbing arborist was familiar, he gripped one part of the climbing line by hand and used foot (Climbing Technology, Bergamo, Italy) and knee (Haas Velox, Oh., USA) ascenders, a Rope Wrench (ISC, Wales, UK), and an eye-and-eye hitch cord (Sterling Rope, Biddeford, Me., USA) tied in a Michoacán hitch and advanced with a Hitch Climber pulley (DMM International, Wales, UK).

For each trial, the climbing arborist tensioned his climbing line, either by engaging the battery-powered ascending device or by hand, and lifted himself off the ground. Then, he paused and minimized residual motion from the initial acceleration to lift his weight; during the pause, which lasted approximately ten seconds, tension in the climbing line and inclinations at both inclinometers remained nearly constant. After pausing, the climbing arborist began his ascent and reached the PSP without stopping. We classified two climbing actions that made up each trial: the pause, when the climbing arborist remained stationary, and the ascent, as the climbing arborist ascended without stopping to the PSP.

2.4. Data processing

Following field data collection, we processed time histories of loading, inclination, and HR. We also computed the duration of each ascent. To normalize loads, we divided them by the climbing arborist's weight on the day of testing. We did this because previous work showed a strong correlation between measured load and a climbing arborist's weight (Kane, 2018). To normalize HR, we divided it by the climbing arborist's RHR on the day of testing. We computed the ratio because it presented a more relatable result—a proportional increase—than the raw HR values. Presenting normalized loads and HR as dimensionless ratios provided results that other climbing arborists can relate to: they can think in terms of multiples of their own weight and RHR. On all days of testing, the climbing arborist's weight (including climbing gear) was 800 N and his RHR was 60 bpm.

From inclination time histories, we computed the resultant inclination at the distal and proximal inclinometers as follows: First, we computed the change in inclination of each axis on each inclinometer by subtracting the equilibrium inclination value of each axis from the measured inclination of the corresponding axis at each time increment. Then, for each inclinometer, we computed its resultant change in inclination at each time increment as the vector sum of the changes in inclination on each axis for the time increment. Computing the resultant change in inclination was necessary because stem morphology prevented a consistent orientation of each inclinometer's axes on different trees. We divided the resultant inclination (°) by the applied load (kN) at the PSP to ensure that differences between treatments (ascending vs. stationary or ascending by hand vs. using the battery-powered ascending device) were attributable to the treatments rather than differences in loading. From normalized time histories of loading and inclination, we computed the 100th and 90th quantiles to consider two possible types of failure: (i) a single, maximum load (100th quantile) causing instantaneous failure and (ii) repeated, lesser magnitude loads (90th quantile) causing fatigue failure. We analyzed only the 100th quantile value of normalized HR. For all response variables, we averaged values from the two trials of each ascent technique on each PSP of each tree.

2.5. Data analysis

For all analyses, we used a mixed model approach, including the effect of tree and its interactions with fixed effects as random effects in the model. For analyses involving the 100th and 90th quantiles of a time history, we created separate models for each quantile. We explored the effect of relevant morphological covariates (described below) on each response variable; if more than one covariate was relevant, we used Akaike's Information Criterion corrected for small sample sizes (AICc) to choose the best one. For analyses including resultant inclination / load, we analyzed values from each inclinometer separately. If the interaction of ascent technique and climbing action was significant ($p < 0.05$), we compared climbing actions (ascending and stationary) within each ascent technique (by hand and using the battery-powered ascender).

To investigate the effect of ascent technique (by hand or using the battery-powered ascending device) and climbing action (stationary or ascending) on normalized loads, we used analysis of variance (ANOVA). To investigate the effect of ascent technique on normalized HR, we used analysis of covariance (ANCOVA) including PSP height as a covariate. To investigate the effect of ascent technique and climbing action on resultant inclination / load at each inclinometer, we used ANCOVA, including covariates expected to influence branch motion: stem diameter above and below the PSP and horizontal distance from the PSP to the main stem. Since deflection of a cantilevered beam subjected to a point load is directly proportional to the cube of the horizontal distance (l) between the application of the point load and the fixed support of the beam and inversely proportional to the fourth power of the beam's diameter (d) (Lardner and Archer, 1994), we also considered as covariates two versions of this ratio (l^3/d_i^4) where the subscript i indicates the location of diameter measurement: one included diameter above the PSP, d_A, and one included diameter below the PSP, d_B. We conducted all analyses using JMP v. 15 (SAS Institute Inc., Cary, N.C.).

3. Results

Fig. 2 shows typical load time histories of each ascent technique; the pause at the beginning of the time history is evident for both techniques. Ascending by hand using the ropewalking technique resulted in a succession of local peaks associated with the climbing arborist's hand and leg motion. The consistency of local peaks throughout the time history is also shown in Fig. 3 which presents the relative time at which the maximum (100th quantile) load in the time history occurred. Maximum loads are more evenly spaced throughout the time history wen ascending by hand.

Ascending using the battery-powered device caused local peak loads at the beginning and end of the ascent with a relatively constant load in between (Fig. 2). Initial peaks in the load time history of battery-powered ascents coincided with the upward acceleration of the climbing arborist following the time when he paused after tensioning the line by lifting himself off the ground. Peaks at the end of the load time history occurred as the climbing arborist stopped the battery-powered device. When he did, the cam that grabs the climbing line locked in place, causing him to descend a small distance, which we did not measure. The consistent occurrence of local peaks at the beginning and end of the time history was reflected in Fig. 3, which shows that all but seven of the maximum loads occurred at the beginning or end of ascents using the battery-powered device.

At both quantiles, normalized loads were greater when (i) ascending compared to remaining stationary and (ii) using the battery-powered ascending device (Table 2). Investigating the significant interaction of climbing action and ascent technique at the 90th quantile, normalized loads were greater when ascending by hand than remaining stationary, but not when using the battery-powered ascending device, but the pattern did not repeat at the 100th quantile (Table 2).

Compared to using the battery-powered ascending device, ascending by hand increased ascent duration by 56% and the climbing arborist's normalized HR by 47% (Table 3). Ascent duration increased with PSP height and there was some evidence that it increased the climbing arborist's HR when he ascended by hand but not using the battery-powered ascending device (Table 3).

At both the 90th and 100th quantiles, distal resultant inclination / load increased as the ratio l^3/d_A^4 increased (Fig. 4, Table 4). For both quantiles and both ascent techniques, distal resultant inclination / load was greater when the climbing arborist ascended compared to remaining stationary (Table 4). But for distal resultant inclination / load at the 90th quantile, the difference between climbing actions only applied when the climbing arborist ascended by hand (Table 4).

The results for proximal resultant inclination / load were similar to those for distal resultant inclination / load (Fig. 5, Table 5), with one exception: At the 90th quantile, proximal resultant inclination / load was similar between climbing actions (Table 5). It was greater when ascending than remaining stationary when the climbing arborist ascended by hand (Table 5).

4. Discussion

This is the first study to investigate the use of a battery-powered ascending device in comparison with ascending by hand. The results for normalized loads and resultant inclinations broadly aligned with simple physical models, which suggests that they are not limited to the sample of PSPs tested, but results should still be applied cautiously because the sample of PSPs was limited to five trees of the same species at a single site. The study also is the first to systematically investigate the effect of PSPs of different sizes and distances from the branch

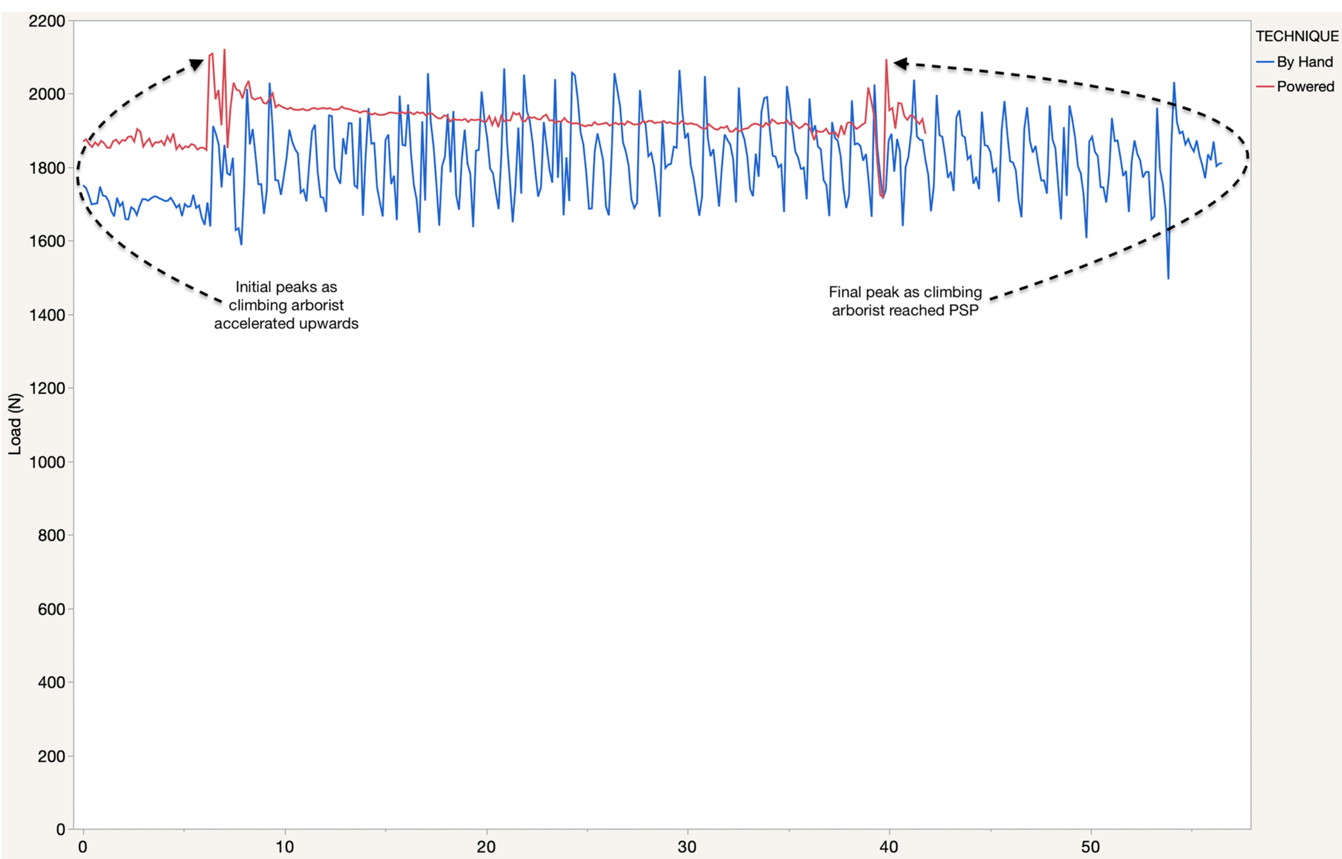

Fig. 2. Load time histories for each ascent technique including (i) a pause at the beginning of the time history during which the climbing arborist remained stationary and the load remained nearly constant (approximately seven seconds), and (ii) the ascent itself, which lasted about fourteen seconds longer when ascending by hand.

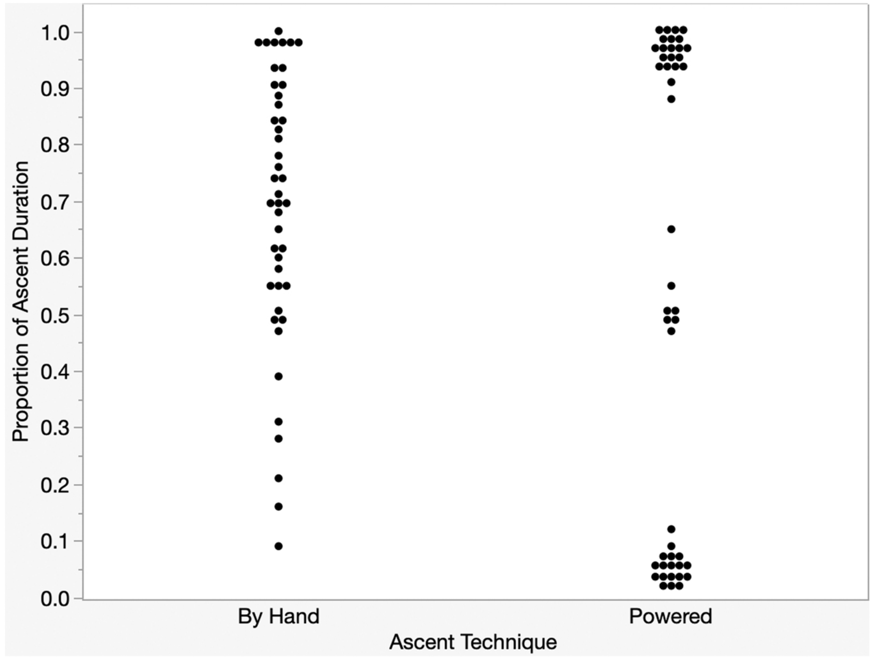

Fig. 3. Scatter plot of the occurrence during the climbing arborist's ascent of loads at the 99.5th and 100th percentiles, expressed as a proportion of the ascent duration, for each ascent technique. Each dot represents a trial.

Table 2
Output of the analysis of variance of the ratio of normalized load[a] at the 90th and 100th quantiles of the load time history, including p-values and least squares (LS) means for significant effects. For the significant interaction of ascent technique and climbing action at the 90th quantile, within each climbing action, LS means followed by the same letter are not significantly different ($p > 0.05$) by the Tukey-Kramer adjustment for multiple comparisons.

		90th Quantile		100th Quantile	
Source	Level	p-value	LS Mean	p-value	LS Mean
Ascent Technique		0.0021		0.0020	
	By Hand		2.22		2.33
	Powered		2.37		2.51
Climbing Action		0.0006		< 0.0001	
	Ascending		2.39		2.61
	Stationary		2.20		2.22
Technique x Action		0.0047		0.0610	
	By Hand Ascending		2.37a		
	Powered Ascending		2.42a		
	By Hand Stationary		2.08a		
	Powered Stationary		2.33b		

[a] Computed as load at the primary support point (N) divided by the climbing arborist's weight (800 N).

Table 3
Output of the analysis of covariance for the effects of ascent technique and a covariate[a] on ascent duration (s) and normalized heartrate[b] (HR). including p-value and, for the significant ($p < 0.05$) effect of ascent technique and the covariate height (m) of the primary support point (PSP), estimates of least squares means or slopes[c], respectively.

		Duration		Normalized HR	
Source	Level	p-value	Estimate	p-value	Estimate
Ascent Technique		0.0039		0.0009	
	By Hand		56		2.2
	Powered		36		1.5
Height		0.0262		0.4301	
			2.0		
Technique x Height		0.4831		0.0514	
	By Hand				0.01
	Powered				-0.02

[a] The covariate that produced the lowest AICc value was height (m) of the primary support point (PSP).
[b] Computed as the climbing arborist's HR during trials divided by his resting HR.
[c] Slope of the best-fit line to predict ascent duration from PSP height.

attachment with the trunk on changes in branch inclination during ascents. A previous study measured changes in PSP inclination as a climbing arborist simulated work movements, but selection of PSPs was not systematic (Kane, 2021).

When the climbing arborist used the battery-powered ascending device, its additional weight increased the ratio of measured load to the climbing arborist's weight by 13%, which is why normalized load was greater when the climbing arborist used the device. But the difference was most plain when the climbing arborist remained stationary. When he ascended, the peak loads that occurred throughout the ascent sometimes equaled or exceeded the peaks associated with impulses at the beginning and end of an ascent using the battery-powered device. The repeated peak loads associated with ropewalking in the present study and previous work (Kane, 2018; Kane et al., 2020) are due to forces exerted by the climbing arborist's arms and legs to accelerate them upwards, and on average, they offset the additional weight of the battery-powered ascending device.

The magnitude of loading is an important consideration when assessing likelihood of PSP failure during an ascent, but other factors are also important. If loads are applied at a frequency similar to the sway frequency of the PSP, dynamic amplification can increase the likelihood of PSP failure even if the load is the same magnitude (Cetrangolo et al., 2018). Dynamic amplification is manifested by greater branch motion for the same magnitude of load, which was the reason for analyzing resultant inclinations / load at each inclinometer. At both inclinometers values of resultant inclination / load were greater when the climber

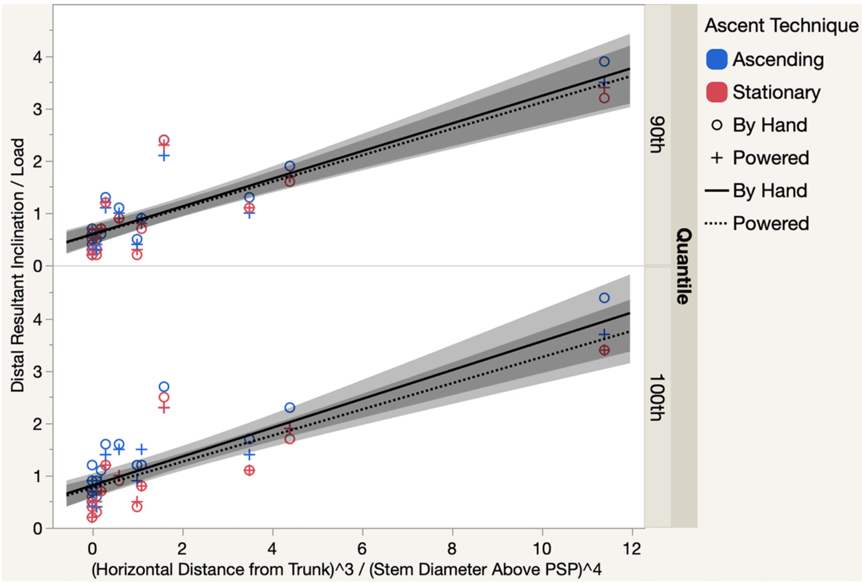

Fig. 4. Scatter plots and best-fit lines at the 90th and 100th quantiles (right-hand vertical axis) for the relationship between distal resultant inclination (°) / load (kN) and l^3/d_A^4, where l is the horizontal distance between the primary support point (PSP) and the trunk (m) and d_A is diameter above the PSP (dm). Table 4 includes (i) least squares means for each combination of climbing action (ascending and stationary) and ascent technique (by hand and powered) and (ii) slopes of best-fit lines. Shaded areas around best-fit lines indicate the 95% confidence interval.

Table 4
Output of the analysis of covariance modeling the effect of ascent technique, climbing action, and a covariate[a] on distal resultant inclination (°) / load (kN) at the 90th and 100th quantiles. Estimates of least squares (LS) means[b] or best-fit line slopes[c] are included below significant ($p < 0.05$) effects or interactions. For the significant interaction of ascent technique and climbing action at the 90th quantile: within each ascent technique, LS means followed by the same letter are not significantly different ($p > 0.05$) by the Tukey-Kramer adjustment for multiple comparisons.

Source	Level	90th p-value	90th Estimate	100th p-value	100th Estimate
Ascent Technique		0.1929		0.0925	
Climbing Action		0.0301		0.0014	
	Ascending		1.05		1.40
	Stationary		0.97		1.02
Technique x Action		0.0124		0.0726	
	By Hand Ascending		1.11a		
	By Hand Stationary		0.93b		
	Powered Ascending		0.99a		
	Powered Stationary		1.00a		
l^3/d_A^4		< 0.0001		< 0.0001	
	Slope		0.26		0.26
Technique x l^3/d_A^4		0.7501		0.4708	
Action x l^3/d_A^4		0.1239		0.2460	
Technique x Action x l^3/d_A^4		0.7580		0.4087	

[a] The covariate that produced the lowest AICc value was l^3/d_A^4, where l is the horizontal distance between the primary support point (PSP) and the trunk (m) and d_A is diameter above the PSP (dm); see Fig. 1.
[b] LS means were calculated for the mean value of the covariate.
[c] Slope of the best-fit line to predict distal resultant inclination (°) / load (kN) from l^3/d_A^4

ascended than remaining stationary because of the additional force needed to accelerate upwards; the difference was more prominent when ascending by hand because repeated local peak loads caused more movement. Values of resultant inclination / load were smaller at the proximal inclinometer because the diameter of the primary branch at the proximal inclinometer was greater than at the distal inclinometer and branch stiffness is proportional to the fourth power of diameter (Lardner and Archer, 1994). But resultant inclinations / load at the proximal inclinometer were still noticeable. In practice, this means that when choosing a PSP, climbing arborists should carefully inspect the primary branch that supports the PSP along its entire length (including the attachment), not just immediately below the PSP.

The likelihood of PSP failure also depends on the type of applied load. As the horizontal distance between the PSP and the attachment of the primary branch to the trunk increased, the leverage, and, in turn, bending stress, on the attachment increased. At both inclinometers, resultant inclinations / load increased in proportion to l^3/d^4 as expected from beam theory (Lardner and Archer, 1994). Taking branch motion as a reasonable surrogate for likelihood of failure, the implication of choosing a smaller diameter PSP that is horizontally farther from the attachment of the primary branch—in the present study, this would be choosing PSP 1 instead of PSP 2 or PSP 3—is a greater likelihood of failure.

The shorter ascent durations and lower normalized HR when ascending with the battery-powered device were intuitive. But additional studies are needed to address important limitations of our work. We only measured ascent duration, but ascent is only one part of tree care operations. Measuring the time to set up each system, perform specific tasks in the tree, descend from the tree, and remove each system would provide a comprehensive assessment of time. It would also be helpful to conduct measurements on a wider variety of trees to include different crown architectures and PSP heights. The presence of branches obstructing a climbing arborist's ascent would presumably increase ascent duration for both ascent techniques as the climbing arborist slowed down to maneuver around them. Branches might also alter loads if the climbing arborist needed to slow down to avoid branches and then re-start his ascent. Our study is also limited to a single climbing arborist; considerably more work needs to be done to consider climbing arborists of different body types, fitness levels, and experience. A better understanding of these factors would help clarify whether ascending by hand or using a battery-powered ascending device was preferable for a particular PSP height, crown architecture, work task, and climbing

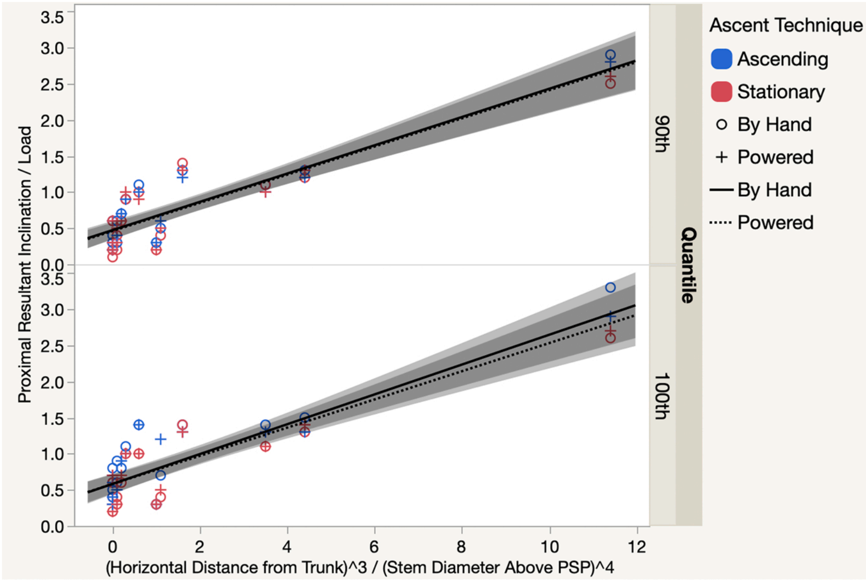

Fig. 5. Scatter plots and best-fit lines at the 90th and 100th quantiles (right-hand vertical axis) for the relationship between distal resultant inclination (°) / load (kN) and l^3/d_A^4, where l is the horizontal distance between the primary support point (PSP) and the trunk (m) and d_A is diameter above the PSP (dm). Table 5 includes (i) least squares means for each combination of climbing action (ascending and stationary) and ascent technique (by hand and powered) and (ii) slopes of best-fit lines. Shaded areas around best-fit lines indicate the 95% confidence interval.

Table 5
Output of the analysis of covariance modeling the effect of ascent technique, climbing action, and a covariate[a] on proximal resultant inclination (°) / load (kN) at the 90th and 100th quantiles. Estimates of least squares (LS) means[b] or best-fit line slopes[c] are included below significant ($p < 0.05$) effects or interactions. For the significant interaction of ascent technique and climbing action at the 90th quantile: within each ascent technique, LS means followed by the same letter are not significantly different ($p > 0.05$) by the Tukey-Kramer adjustment for multiple comparisons.

		90th		100th	
Source	**Level**	p-value	Estimate	p-value	Estimate
Ascent Technique		0.2858		0.4625	
Climbing Action		0.1317		0.0170	
	Ascending				1.01
	Stationary				0.80
Technique x Action		0.0199		0.0739	
	By Hand Ascending		0.84a		
	By Hand Stationary		0.74b		
	Powered Ascending		0.79a		
	Powered Stationary		0.77a		
l^3/d_A^4		< 0.0001		< 0.0001	
	Slope		0.20		0.20
Technique x l^3/d_A^4		0.6528		0.5775	
Action x l^3/d_A^4		0.2332		0.3970	
Technique x Action x l^3/d_A^4		0.6742		0.2572	

[a] The covariate that produced the lowest AICc value was l^3/d_A^4, where l is the horizontal distance between the primary support point (PSP) and the trunk (m) and d_A is diameter above the PSP (dm); see Fig. 1.
[b] LS means were calculated for the mean value of the covariate.
[c] Slope of the best-fit line to predict distal resultant inclination (°) / load (kN) from l^3/d_A^4

arborist.

5. Conclusion

Using the battery-powered ascending device reduced the ascent duration and normalized HR of the climbing arborist. And although loads measured at the PSP were greater when using the battery-powered ascending device, this was most plain when the climbing arborist remained stationary, not while ascending. Neither did the battery-powered ascending device increase resultant inclination / load at either inclinometer. Instead, at both inclinometers, resultant inclination / load, which reflects the likelihood of failure, was primarily influenced by l^3/d^4. Because of this, climbing arborists should carefully inspect a PSP—including well below it—and consider its stem diameter and horizontal distance from the branch attachment.

CRediT authorship contribution statement

Brian Kane: Conceptualization, Methodology, Data curation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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