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Forces generated in rigging trees with single and co-dominant stems

Brian Kane*

Department of Environmental Conservation, 160 Holdsworth Way, University of Massachusetts, Amherst, MA 01003, United States

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ABSTRACT

Despite the inherent danger that accompanies rigging trees, very few studies have investigated this important aspect of arboricultural practice. Following work we completed in 2009, there appear to be no studies that address limitations of our work. Using similar methods to our original work (Kane et al., 2009), we explored additional aspects of rigging and built upon our previous study, considering trees with co-dominant stems and measuring acceleration of the stem near the rigging block. The mass of the piece was the best predictor of force in the rigging, superseding other variables related to the piece (length, diameter) or the rigging (length of rope, fall distance, angle and depth of the notch). Force per unit mass was greatest when "shock loading" the rigging with pieces of the branchless trunk. Friction in the block appeared to be greater than previously considered, which reduces the effectiveness of the block in converting kinetic energy of the rigged piece to elastic strain in the rigging rope. Since the mechanics of rigging is complicated, more empirical data are needed to lend insight and help practitioners work more safely.

1. Introduction

In a previous paper, we measured the forces (in the rigging rope and at the block) and stresses (in the trunk) induced by "shock load" rigging of red pines (*Pinus resinosa* Ait.) (Kane et al., 2009). In that work, we demonstrated (i) the importance of mass to predict rigging-induced forces and (ii) that predicting forces from a theoretical analysis derived for falling rock climbers is less applicable when rigging trees. We also highlighted a difference in force per unit mass (i.e., acceleration) when rigging tops as opposed to pieces of the branchless trunk. Our previous work, which was largely consistent with industry best practices (Donzelli and Lilly, 2001), provided guidelines for practitioners to rig trees safely and was a useful starting point for future investigations. But it was limited by tree morphology, cutting all trunk pieces (except tops) to the same length, and not measuring tree response near the point where the rigging block was attached to the tree. Even though industry best practices are available (Donzelli and Lilly, 2001), there are very few empirical data to support them.

Since our original work, a review of the literature found no additional studies that addressed the limitations of our work or further explored our findings. Detter et al. (2008) is the only other report of forces measured in rigging. Yet rigging remains a common and dangerous practice that has resulted in tree worker fatalities (Ball and Vosberg 2004). The large forces and stresses we presented in 2009 can cause failure of trees or branches to which rigging gear is attached, as well as the gear itself. Rigged pieces often have large momentum because of their mass, velocity, or both. Some of the few empirical data describing aspects of rigging also may be less applicable, because experimental conditions did not mimic rigging conditions. An example of this is Donzelli's (1999) data on friction coefficients of rigging blocks, which were determined by raising and lowering weights rather than rigging cut pieces from a tree. Friction coefficients ranged from 0.049 to 0.99 for three different blocks and decreased non-linearly when lowering increasingly large loads (Donzelli 1999).

Using data collected in 2006 and 2007 [some of which were published in Kane et al. (2009)] and data collected subsequently (in 2008 and 2010), we attempt in the current paper to address some of the limitations of previous work on rigging. In particular, in subsequent tests, we rigged pieces of two additional lengths, tested trees with co-dominant stems, and measured accelerations near the cut made to remove rigged tops and pieces.

2. Materials and methods

In May and June of 2008 and 2010, we repeated the methods of Kane et al. (2009) with several important changes. In the original work, we rigged branched tops and branchless trunk pieces with a rope passed through an arborist block (ISA Ltd., Glasgow, Scotland) attached to the trunk with a sling (Amsteel®, Samson Rope Technologies, Inc., Ferndale, WA, USA) just below the top or piece being removed. The rope was anchored to a Port-A-Wrap (Buckingham Mfg., Binghamton, NY, USA) at the base of the tree so that the rigged top or piece would shock load

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* Corresponding author.
E-mail address: bkane@eco.umass.edu.

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Table 1
Sample size of branched tops and branchless trunk piece, mean (standard deviation in parentheses) trunk diameter at 1.37 m above ground (DBH) and tree height for red pines tested in the original (2006–2007) and current (2008, 2010) studies.

Year of Data Collection	Tops	Pieces	DBH	Height
2006–2007	13	52	30.6 (4.6)	21.6 (1.6)
2008, 2010	12	42	37.8 (6.0)	21.4 (1.9)

the rigging gear. We measured forces at the block (F_B) and Port-A-Wrap with dynamometers (Dillon EDxtreme, Avery Weigh-Tronix, Fairmont, MN, USA). Force measured at the Port-A-Wrap reflected tension in the fall of the rope (T_F), the length of rope between the Port-A-Wrap and the block. The lead of the rope is between the block and the cut piece or top. We also measured the proximal diameter, length, mass, and center of gravity of each top and piece—all pieces were cut to the same length (1.83 m). We also measured the fall distance (twice the distance from the sheave of the block to the center of gravity of the top or piece) and length of rope in the rigging (the distance between the two anchor points of the lowering rope—at the base of the tree and to the piece or top being rigged). When removing tops and pieces, we randomly assigned a notch depth (deep or shallow) and angle (narrow or wide). When removing pieces, but not tops, we also used bypass cuts.

In 2008 and 2010, we tested twelve additional red pines—six each year—growing in the same location as the original work (USDA Hardiness Zone 5b). In 2008, we tested trees with a single stem; in 2010, we tested trees with co-dominant stems that arose between three and six meters above ground. Trees were not near other trees and the trunks had no decay or cracks. Table 1 includes sample size, trunk diameter 1.37 m above ground (DBH) and tree height. In 2008, we also attached tri-axial accelerometers (G-link, Microstrain Inc., Williston, VT, USA) to the trunk within a meter of where we cut each piece to remove it. The accelerometers sampled at 32 Hz and wirelessly transmitted data to a base station connected to a laptop on the ground.

In 2008, after removing the top of a tree, we removed four additional pieces from each tree; in 2010, we removed between two and four additional pieces depending on the length of the co-dominant stem. We randomly assigned the length of pieces as 1.22 m or 2.44 m in 2008 and 1.22 m, 1.83 m, or 2.44 m in 2010. We removed tops and pieces in the same way as the original work: making a directional notch of randomly assigned angle and depth. We analyzed measured angles and depths; the latter was expressed as a percentage of stem or trunk diameter at the cut. To remove pieces (but not tops), we also used bypass cuts, which are made by cutting partially through the piece on opposite sides but separated by a large enough axial distance so that even when the cuts overlap or bypass one another, the piece does not release from the trunk. In the analyses, we considered the angle of bypass cuts to be 0° but did not include their depth. In 2010, for some pieces, we did not secure the lowering rope at the Port-A-Wrap, but rather lowered the piece in a controlled fashion by gradually slowing its descent and stopping it just above the ground. In practice, this is known as “letting a piece run,” the preferred method to avoid shock loading.

2.1. *Analysis I*

We used stepwise multiple regression [PROC REG in SAS (Cary, NC, USA)] to determine which independent variable(s) (mass, length, and fall distance of the rigged top or piece; length of the lowering rope in the rigging system; angle and depth of the notch) best explained variation in F_B and F_B/T_F. For Analysis I, we (i) pooled data from Kane et al. (2009) and trees tested in 2008; (ii) analyzed tops and pieces separately because Kane et al. (2009) showed that there was a different relationship between force and mass for tops and pieces; (iii) analyzed natural-log transformed values of notch depth (which was expressed as a percentage of the trunk diameter at the point of the cut) and notch angle (which was bounded between 0° and 180°); and (iv) calculated variance inflation factor to test for multi-collinearity of independent variables. Since practitioners can only estimate the mass of a piece before removing it and mass was previously shown to be the best predictor of F_B (Kane et al., 2009), we developed a second multiple regression model to predict F_B from only the basal diameter and length of cut pieces and tops.

We previously reported the stepwise model predicting F_B (Kane et al., 2009), and data collected in 2008 (which added pieces 1.22 m and 2.44 long to the previous dataset that included only pieces 1.83 m long) accounted for only 32% percent of the sample in the current analysis. Thus, we repeated the stepwise model including only data collected in 2008 to compare it with the model including pooled data from 2008 and data reported in Kane et al. (2009). For the same reason, we re-analyzed the simple linear regression between F_B and T_F (described in Analysis II) including only data collected in 2008. It was not necessary to do this for any other analyses because although some of the pooled data in the remaining analyses were collected in 2006 and 2007, they were not previously analyzed and reported in Kane et al. (2009). For all analyses, we examined plots of (i) residuals and (ii) observed versus predicted values and found no evidence of bias or heteroscedasticity.

2.2. *Analysis II*

With the same pooled data as Analysis I, we conducted additional analyses. First, including tree as a random effect in the model, we used a one-way analysis of variance (ANOVA) to determine whether F_B per kg mass varied among pieces of different length (1.22 m, 1.83 m, and 2.44 m). For the ANOVA, we used PROC MIXED in SAS. Secondly, we used simple linear regression (PROC REG) to compare F_B with T_F. We calculated the mean ratio F_B/T_F, and used a *t*-test (PROC TTEST in SAS) to determine if the means for tops and pieces were different, for use in the following analysis.

Since F_B is the vector sum of tensions in the lead (T_L) and fall of the rope, both (i) the amount of friction in the block—which will reduce T_F compared to T_L, and (ii) the angle (α) from vertical that T_L makes at the time of maximum tension, will affect F_B. We did not measure friction in the block and α. Instead, to calculate the ratio T_F/T_L and estimate friction in the block while rigging, we used the mean of F_B/T_F and assumed that the fall of the rope remained parallel to the trunk (which we observed on video footage of the tests). Then, we used vector addition to calculate T_F/T_L for $20° \leq \alpha \leq 50°$. The range of α values is an expansion of the range of values that Detter et al. (2008) observed.

2.3. *Analysis III*

Pooling data from (i) Kane et al. (2009), (ii) trees with a single stem measured in 2008, and (iii) trees with co-dominant stems measured in 2010, and including the random effect of “tree”, we used a one-way ANOVA (PROC MIXED) to determine whether F_B per kg mass of the rigged piece or top varied among the following six rigging scenarios: (1) using a felling notch to remove the top of a single stem tree, (2) using a felling notch to remove the top of a co-dominant stem while retaining the other co-dominant stem, (3) using a felling notch to remove pieces from a single stem, (4) using a bypass cut to remove pieces from a single stem, (5) using a felling notch to remove pieces from a co-dominant stem while retaining the other co-dominant stem, (6) lowering pieces from a co-dominant stem in a controlled fashion while retaining the other co-dominant stem (“letting the piece run”). We used Tukey’s Honestly Significant Difference test for multiple comparisons of least squares means.

2.4. *Analysis IV*

On trees tested in 2008, we examined each time history of