Rigging is one of the most dangerous aspects of arboriculture, yet there are no robust studies of the forces and stresses generated during rigging. Compounding the inherent danger of rigging is the structurally-deficient condition of many trees that are removed using rigging. Red pines (*Pinus resinosa* Ait.) (*n* = 13) were removed using conventional techniques, and forces at the block and in the rope were measured as the top, and four subsequent pieces were rigged with a block and Port-A-Wrap. Stress in the trunk at breast height was calculated from strain measurements and each tree’s modulus of elasticity. Multiple regression was used to determine which independent variables (mass of piece, fall distance and fall ratio, notch angle and depth) best predicted forces. Tops and pieces exhibited different relationships with mass, which was the best predictor of force at the block and tension in the rope. Other variables were not as important and exhibited counter-intuitive relationships with forces. There were few differences in stress generated when removing tops and pieces, which appeared to be due to greater deflection higher in the trunk when tops were removed.

Key Words. Rigging; Trunk Stress; Biomechanics.
METHODS AND MATERIALS

Thirteen red pines (Pinus resinosa Ait.) growing in a plantation in Amherst, MA, USA were selected according to their physical similarity, proximity to an access road, lack of structural defects, and distance from other trees. The trees averaged 30.6 cm (1 ft) dbh [4.57 cm (1.8 in) standard deviation] and 21.6 m (70.87 ft) tall [1.64 m (5.38 ft) standard deviation]. Each was rigged for removal in accordance with conventional arboricultural practice. In particular, lateral branches were removed until a top remained that was small enough to remove without risking failure of the rigging gear or the tree. A block [ISC Ltd., Glasgow, Scotland, 2000 kg (440.92 lb) working load limit, 20 mm (0.79 in) maximum rope diameter] was attached with a 12.7 mm (0.5 in) Amsteel® (Samson Rope Technologies Inc., Ferndale, WA) sling approximately 7-10 cm (2.76-3.94 in) below where the cut would be made to remove the top from the trunk. A notch was made in the intended felling direction and the lowering rope [12.7 mm (0.5 in) diameter Stable Braid (Samson Rope Technologies Inc., Ferndale, WA)] was run through the block and tied off to the top with a marl and a running bowline. The felling cut was made opposite the notch and the top was pulled by hand, as necessary, with a tag line to ensure that it fell in the appropriate direction. The lowering rope was secured to the base of the tree by a steel Port-A-Wrap (Buckingham Mfg., Binghamton, NY), which was also attached to the tree by a 12.7 mm diameter Amsteel sling. Securing the rope in this fashion caused the top to stop abruptly, generating the intended large forces. Removal of tops and pieces was videotaped with a digital video camcorder (Canon GL2, Jamesburg, NJ).

After the top was removed, its length, mass, and center of gravity were determined. The trunk diameter at the base of the top was measured both parallel and normal to the direction of fall. Four additional pieces were removed from each tree, except for two trees, for which three and five additional pieces were removed, respectively. Not including the top, pieces were 1.83 m (6 ft) long, and were removed in the same fashion as the top. The mass, diameters (at the top and bottom of the piece), and center of gravity were also determined for each piece.

Forces at the block and Port-A-Wrap were measured with dynamometers [Dillon EDXtreme, 44 kN (10,000 lbf) and 22 kN (5,000 lbf) capacity, respectively, accurate to 0.1% of capacity]. The peak load was recorded by each dynamometer, sampling at 60 Hz.

The amount of rope in the rigging system and distance of fall were measured for the top and each piece so that the fall factor (see equation 1) could be calculated. Assuming minimal slack in the lowering rope, the distance of fall is twice the distance from the pin at the center of the sheave of the block to the center of gravity of the piece. Placement of a dynamometer between the sling and the block increased the fall distance compared to a work situation. The length of rope in the system is the distance from the Port-A-Wrap to the marl tied to the piece. The value for k for the lowering rope was determined using Equation 2, and the following values: P = 4.6 kN (1,034 lbf), which is 10% of the average tensile strength as provided by the manufacturer (Samson 2008), and L/x = 90.9 [rope extension at 10% of average extension (m)], and so must be considered only an estimate. The tension in the rope must be doubled to estimate the force in the block and sling, which is transferred to the tree at the rigging point. The force at the block would be somewhat less than twice the tension in the rope because friction in the block would reduce the tension in the rope between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999).

For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999). For a 227 kg (500 lb) mass, Donzelli (1999) determined that the reduction in rope tension between the block and the friction device that anchors the rope at the base of the tree (Donzelli 1999).
E = \frac{\sigma}{\varepsilon}.

The value of E reflects the entire tree, including rotation of the root plate as the tree bends. This value was likely less than E values of the wood of the tree, but more consistent with a tree in situ. Strains measured during rigging operations were converted into stresses using each tree’s empirically-determined E value and a re-arranged version of equation 4:

\sigma = E\varepsilon.

Two stress values were collected for each top and piece, one measured parallel and one measured normal to the direction of fall. Measured strains reflect the dynamic modulus of elasticity, which, for timber is typically 5%–10% greater than the static elastic modulus (Bodig and Jayne 1993). Thus, the actual rigging-induced stress was likely 5%–10% greater than presented. The percentage of the trunk cross-section that could be decayed was calculated by mathematically reducing the cross-section (i.e., reducing its second moment of area) until the maximum rigging-induced stress in the trunk equaled the strength of the tree. Strength of the tree was taken as 80% of the lower confidence interval of the average green wood strength of red pine from the Wood Handbook (Green et al. 1999). Previous studies have demonstrated that the strength of trees is approximately 80% of the strength of wood samples (Fons and Pong 1957; Kane and Clouston 2008).

Felling notches were assigned randomly with respect to width and depth. For tops, notches were classified as wide (i.e., >60º) or narrow (i.e., <30º); and as deep (i.e., notch depth > 50% of diameter at the cut) or shallow (i.e., notch depth < 50% of diameter at the cut). In practice, notch depth and angle varied from the intended classification, so measured values were used in the analysis. For pieces, the classifications were the same, except that bypass cuts were also tested. Bypass cuts were considered to have an angle of 0º and depth was not considered in the analysis. The theoretical principle behind testing notches was that notch width and depth would presumably affect the time it took the hinge to break. This, in turn, would affect both the time of free fall and how much of the potential energy of the piece was converted to strain energy in the trunk.

Using PROC REG of the SAS statistical analysis software (v. 9.1, SAS Institute, Cary, NC), two multiple linear regression models were built to determine which independent variables best predicted both force at the block and tension in the rope. The first model considered the following independent variables, chosen on the basis of their physical or practical importance: mass of piece, fall distance (which is twice the distance from the center of gravity of the piece to the sheave of the block), length of rope in the rigging, notch depth, and notch angle. A second model mimicked the first, but considered fall factor instead of its individual components. Preliminary investigation of scatter plots revealed 1) mass strongly influenced force, and 2) the forces generated by tops and pieces exhibited different relationships with mass. The latter observation was tested using dummy variables and simple linear regression to compare slopes and intercepts of the best-fit lines for forces generated by tops and pieces as predicted from mass. As a result of the preliminary analyses, both multiple linear regression models were repeated twice: first, tops and pieces were analyzed separately; second, force was divided by mass (the quotient is acceleration) and mass was not considered in the regressions. The MAXR option (SELECTION=MAXR) was used to add components to each model in a stepwise fashion.

Multiple linear regression was also used to investigate whether pertinent physical parameters such as mass, height of piece above ground, fall distance, length of rope, (fall factor was analyzed in a subsequent model as with the models to predict force), diameter at breast height, notch angle, or notch depth influenced stress, but tops and pieces were not analyzed separately. An analysis of variance (ANOVA) was used to determine whether force at the block (and force divided by mass), tension in the rope (and tension divided by mass), stress, strain, mass and length of pieces, and fall distance varied among pieces. Simple linear regression was used to investigate the relationship between 1) predicted force from equation 1 and measured force, and 2) force at the block and tension in the rope.

RESULTS

Force at the block and tension in the rope increased at a greater rate with increases in mass for pieces than for tops (Figure 2). Fall factor was not a significant predictor of force at the block, tension in the rope, or the normalized versions of those measures (i.e., after they were divided by the appropriate mass), so the remaining results refer only to the regression models that included distance of fall and rope length as separate variables. For all trees, the mean modulus of elasticity (standard deviation in parentheses) was 4,674 (1,440) MPa [678 (209) ksi] when measured in the direction of probe 1 and 4,569 (993) MPa [663 (144) ksi] for probe 2, a difference of 2.2%.

![Figure 2. Prediction of force at the block by mass of the piece; the equation for pieces (■) was force = 89.2*mass+1644 (r² = 0.80); the equation for tops (*) was force = 57.4*mass+84 (r² = 0.94). Although the intercepts for the two prediction equations were not significantly different, the slopes were (P < 0.0001). Slopes and intercepts for the prediction of rope tension from mass were also different between tops and pieces.](image-url)

**Force at the Block**

For pieces, mass was the best and only significant predictor of force at the block, and the regression model was fairly robust.
Tension in the Rope

For tops and pieces, force at the block was slightly more than double the tension in the rope (Figure 3). For pieces, mass was the best predictor of tension in the rope (Table 1). Depth of the notch was a significant, but less important predictor, and, counter-intuitively, the relationship was inversely proportional (Table 1). The regression model was slightly less robust than the model predicting force at the block: force at the block was greater for tops and piece 4 than for piece 1, but did not differ among any other pieces (Table 2). In contrast, normalized force at the block was least for tops, and did not vary among the remaining pieces (Table 2).

**Table 1. Results of multiple regression analyses to predict force at the block (FB) and tension in the rope (T) for Pieces and Tops.**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Estimate (SE)</th>
<th>P</th>
<th>Contribution to model</th>
<th>Intercept</th>
<th>Estimate (SE)</th>
<th>P</th>
<th>Contribution to model</th>
<th>Intercept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>4.815 (3.429)</td>
<td>0.184</td>
<td>-1,354 (1,955) 0.4922</td>
<td>5.088 (3.681) 0.2094</td>
<td>3.294 (2.165) 0.1720</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mass</td>
<td>84.6 (6.71)</td>
<td>0.001</td>
<td>77.6 36.8 (3.81) 0.0001</td>
<td>59.3 (4.63) 0.0001</td>
<td>24.0 (2.73) 0.0001</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fall distance</td>
<td>-33.9 (63.7)</td>
<td>0.5969</td>
<td>0.1 6.36 (36.2) 0.8612</td>
<td>-557 (199) 0.0268</td>
<td>-32.3 (154) 0.8394</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cut angle</td>
<td>5.53 (5.92)</td>
<td>0.3552</td>
<td>-1.24 (3.36) 0.7139</td>
<td>8.29 (20.3) 0.6949</td>
<td>-9.34 (11.9) 0.4592</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rope length</td>
<td>-33.9 (63.7)</td>
<td>0.5969</td>
<td>0.1 6.36 (36.2) 0.8612</td>
<td>-557 (199) 0.0268</td>
<td>-32.3 (154) 0.8394</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table 2. Means (standard deviation in parentheses) for variables of interest: force at the block (FB), tension in the rope (T), fall distance (Fall of Piece), and mass (Mass).**

<table>
<thead>
<tr>
<th>Piece</th>
<th>n</th>
<th>FB (N)</th>
<th>T (N)</th>
<th>AccelFB (m/s²)</th>
<th>AccelT (m/s²)</th>
<th>Mass (kg)</th>
<th>Fall Distance (m)</th>
<th>Fall Ratio</th>
<th>Length of Piece (m)</th>
<th>Stress (kPa)</th>
<th>Strain (mm/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top</td>
<td>13</td>
<td>8,783</td>
<td>3,347</td>
<td>58.5</td>
<td>22.4</td>
<td>152</td>
<td>7.40</td>
<td>0.56</td>
<td>6.27</td>
<td>9.202</td>
<td>0.0021</td>
</tr>
<tr>
<td>1</td>
<td>13</td>
<td>5,439</td>
<td>(4,303) a</td>
<td>1,734 a</td>
<td>(9.22)</td>
<td>(5.19) a</td>
<td>(72.7) a</td>
<td>(1.38) a</td>
<td>(0.10) a</td>
<td>(6,433) a</td>
<td>(0.012) a</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>7,057</td>
<td>3,123</td>
<td>48.2</td>
<td>52.9</td>
<td>126</td>
<td>3.47</td>
<td>0.36</td>
<td>1.83</td>
<td>5,388</td>
<td>0.0011</td>
</tr>
<tr>
<td>3</td>
<td>13</td>
<td>5,439</td>
<td>(1,110) abc</td>
<td>(14.25) b</td>
<td>(17.6) b</td>
<td>(21.5) b</td>
<td>(0.16) b</td>
<td>(0.05) b</td>
<td>(0.00) b</td>
<td>(5,314) b</td>
<td>(0.004) b</td>
</tr>
<tr>
<td>4</td>
<td>13</td>
<td>7,225</td>
<td>(2,015) abc</td>
<td>(1,014) abc</td>
<td>(15.2) b</td>
<td>(8.64) c</td>
<td>(22.0) b</td>
<td>(0.16) c</td>
<td>(0.07) c</td>
<td>(4,010) ab</td>
<td>(0.006) b</td>
</tr>
</tbody>
</table>

Because stress was measured both normal and parallel to the direction of fall, the sample size was 25 (23 for piece 4 since one tree only had 3 pieces after the top).
when loaded at the rigging point. Large deflections higher up a tapered, cantilevered beam is proportional to the cube of its diameter above ground. Beam mechanics predicts that the deflection of the data, as stress generated by tops and all but the smallest pieces was similar. This disparity was an artifact of experimental procedure, as stress was measured on the trunks 1 m above ground. Future investigations should attempt to measure deflection near the rigging point.

It was not surprising that mass was by far the best predictor of force at the block and tension in the rope for both tops and pieces, since it influences potential energy. It was initially surprising, however, that predictions of force at the block and tension in the rope were different for tops and pieces. Since trunks were longest and most slender when tops were removed, elementary beam mechanics predicts that trunk deflection will be greatest for tops because deflection is proportional to the cube of the length and inversely proportional to the fourth power of the diameter of a beam (Lardner and Archer 1994). Video observations also support this idea, which reflects a greater proportion of potential energy of tops doing work to deflect the trunk. Thus, a smaller proportion of potential energy can do work to elongate the lowering rope. The findings that tops had similar values for force at the block and tension in the rope to other pieces (except for piece 1) but the smallest normalized values for force at the block and tension in the rope also supports this reasoning. Drag on the top as it fell may also have slowed its descent, and while this effect was not quantified, Detter (2008) observed reduced velocity of removed pieces when they still had branches attached.

Other variables expected to influence force at the block and tension in the rope (e.g., notch depth and angle, distance of fall, and length of rope in the system) were less influential. Fall factor did not predict force at the block or tension in the rope because equation 1 is most appropriate when the rope is elastic. Ropes used in rock climbing [for which equation 1 was originally derived (Pavier 1998)] are designed to stretch in order to reduce tension in the rope as it decelerates and stops a falling climber. Typical elongation in a rock climbing rope is 20%–30% during a fall, whereas the elongation of Stable Braid is only 1.1% at 10% of tensile strength (Samson 2008). Elongation tends to be bi-modal, with greater elongation when the rope is new and less elongation after the rope has been broken in (McLaren 2006). Since the rope used in the present study was not new, it is doubtful that elongation exceeded 1.1%. However, some elongation would occur due to tightening of knots and slippage of the slings that held the block and port-a-wrap in place on the trunk. Indeed, for two tops, the force at the block was great enough to strip bark from the trunk as the sling and block slid about 0.5 m down the trunk. Incidentally, the latter may have also been a source of energy loss (due to friction).

Distance of fall did not predict force at the block and tension in the rope for pieces because all pieces were the same length, an artifact of experimental design. Since tops and pieces behaved differently, it was not prudent to perform a multiple regression with tops and pieces together, because it was not possible to separate the other effects from fall distance. For tops, however, the paradoxical finding that distance of fall was inversely proportional to force at the block and tension in the rope may also be attributed to greater trunk deflection as the top released from the trunk, but careful measurements of trunk deflection will have to be made before this attribution can be confirmed.

Depth and angle of the notch were also expected to influence force at the block and tension in the rope because shallower and deeper notches presumably cause the cut piece to release sooner from the trunk, which means they would have greater velocity (and thus would require greater stopping force). The data do not generally support this intuition, and while depth of the notch was

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a significant predictor of tension in the rope for pieces (and marginally significant for tops), the relationship was, paradoxically, inversely proportional. Intuitively, one expects that a deeper notch would cause the piece to release from the trunk sooner, which would increase the time it fell, and thus its velocity, before the rope stops it. It is unclear why this occurred, but careful investigation of the extent to which the depth and angle of the notch influence the length of time before the piece releases from the trunk should lend insight into this phenomenon. Detter (2008) observed possible differences in rotation of the cut piece depending on the type of notch (conventional or Humboldt), but there were too few observations and no statistical analyses to draw meaningful conclusions.

Notch depth and angle, as well as fall distance, are theoretically less important than mass, since velocity is proportional to the square root of the fall distance, while acceleration required to stop the piece is directly proportional to mass. The poor prediction of normalized force at the block and tension in the rope by any of the variables in those models supports the idea that mass was far more influential than either fall distance or depth and angle of the notch. Assuming that the intuitive expectation that the depth and angle of the notch influence the force required to stop a falling piece, it is unclear that their influence would supersede the influence of fall distance, because taking a longer piece increases fall distance linearly. Practically speaking, climbers are advised to 1) take a less massive piece, 2) take a shorter piece, 3) keep the block close to the cut, and 4) avoid slack in the lowering rope, since these factors will have a greater impact on stopping force than notch depth and angle. In many situations, however, any one of these recommendations may not apply or, worse, may cause a greater risk to the climber. For example, situations often arise in rigging when the climber intentionally adds slack to the rigging to avoid a cut piece from swinging back into the climber. Thus, the recommendations should not supersede a climber’s good judgment when deciding on how to set the rigging point might cause failure at a different location than where stress was measured. A climber’s experience may still be more valuable in determining whether a tree is safe to climb, but the hollow cross-sections estimated above can provide some valuable in determining whether a tree is safe to climb, but the hollow cross-sections estimated above can provide some guidance in assessing the safety of rigging a particular tree.

CONCLUSION
We have demonstrated the importance of mass in predicting rigging-induced forces, as well as interesting differences between tops and pieces with respect to force and stress. We have also shown that predicting force from the theoretical analysis derived for falling rock climbers is less applicable in rigging trees. Such disparities highlight the need for additional studies to assess the forces and stresses generated during rigging. Future areas of investigation include exploring differences between tops and pieces, measuring deflection at the rigging point, comparing pieces of similar mass while varying fall distance, and more precisely measuring the effect of notches and hinges on movement of the piece after cutting. Finally, a more robust analysis with respect to the dynamic response of trees during rigging would be most helpful.

Acknowledgments. The authors gratefully acknowledge the assistance of Ed Carpenter, Melissa Duffy, Mollie Freilicher, Marcy Gladys, Dan Goodman, and Noel Watkins, as well as two anonymous reviewers for helpful comments on earlier versions of the manuscript.

\[ t = m \times d + m, \]

where \( d \) is the distance of fall. This guideline overestimated rope tension by 82% for tops but only 18% for pieces, which underscored the previously-described difference between tops and pieces with respect to the forces generated.

A final practical application of the findings was to estimate the allowable amount of decay in the trunk before risking tree failure during rigging. For concentric decay columns, tree failure would have occurred when the cross-section was 60% hollow; for decay columns offset to the periphery of the cross-section, tree failure would have occurred when the cross-section was only 45% hollow. These values must be taken with extreme caution, since stress was only measured at the base of the tree and the values presented are likely smaller than actual stress since we used the static elastic modulus in equations 4 and 5. The impact of the piece being removed on the trunk below the rigging point might cause failure at a different location than where stress was measured. A climber’s experience may still be more valuable in determining whether a tree is safe to climb, but the hollow cross-sections estimated above can provide some guidance in assessing the safety of rigging a particular tree.

\[ t = m \times d + m, \]
LITERATURE CITED

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Résumé. Le gréement est l’un des aspects les plus dangereux en arboriculture, quoiqu’il n’y a pas d’études robustes sur les forces et les stress générés durant le gréage. Une composante du danger inhérent au gréement est la condition structurellement déficiente de plusieurs arbres qui sont abattus au moyen d’un gréement. Des pins rouges (Pinus resinosa) (n = 13) ont été abattus au moyen de techniques conventionnelles et les forces au niveau du bloc et de la corde ont été mesurées au niveau du sommet ainsi que de quatre pièces (ou sections) subséquentes ont été gréées et descendues à l’aide d’un système approprié. Le stress sur le tronc au niveau du D.H.P. a été calculé au moyen de mesures de tension ainsi que le module d’élasticité de chacun des arbres. Une régression multiple a été employée pour déterminer quelles variables indépendantes (masse de la pièce, hauteur de chute et ratio de hauteur, angle et profondeur de l’encoche d’abattage) prédévait le mieux les forces. Les sommets et les pièces présentaient différentes relations avec la masse qui était la meilleure variable de prédiction de la force au niveau du bloc et de la tension sur la corde. Les autres variables n’étaient pas aussi importantes et présentaient des relations mesurables plus intuitives avec la force. Il y avait peu de différences dans le stress généré lorsque les sommets et les pièces étaient coupées, ce qui semblait être dû à une plus grande défécion de la partie supérieure du tronc lorsque les sommets étaient coupés.


Resumen. El cordaje es uno de los más peligrosos aspectos de la arboricultura, aunque no hay estudios robustos de las fuerzas y tensión generados durante el aparejo. La composición del peligro inherente del cordaje está en la condición estructuralmente deficiente de muchos árboles que son removidos usando aparejos. Trece pinos rojos (Pinus resinosa Ait.) fueron derribados usando técnicas convencionales, cuatro piezas fueron removidas con una polea y un ancla y se midieron las fuerzas en la polea y en la cuerda. Se calculó la tensión en el tronco, a la altura del pecho, de mediciones de resistencia y módulos de elasticidad de los árboles. Se usó regresión múltiple para determinar cuál variable independiente (masa de la pieza, distancia de la caída y relación de caída, ángulo y profundidad del corte) predijo mejor las fuerzas generadas. Las puntas y las piezas exhibieron diferentes relaciones con la masa, las cuales fueron las mejores para predecir la fuerza en la polea y en la tensión en la cuerda. Otras variables no fueron tan importantes y no exhibieron relaciones con las fuerzas. Hubo pocas diferencias en el estrés generado cuando se removieron las puntas y piezas, lo cual parece deberse a la mayor deflexión en el tronco cuando las puntas son removidas.

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