An Apple Tree Branch Pruning Analysis

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SUMMARY. The torque required to cut branches is an important parameter for designing a robotic end-effector for pruning apple (*Malus × domestica*) trees. In this study, the branch cutting torque was measured because it is important for the future development of a robotic pruning end-effector. To measure the branch cutting torque, a force-measuring sensor was integrated with a manual shear pruner. An inertial measurement unit sensor was also used to monitor the angle between the shear blades and the branch. Field tests were conducted for ‘Fuji’, ‘Gala’, ‘Honeycrisp’, and ‘Golden Delicious’ trees, and the cutting torque was calculated for different branch diameters. The results indicated that the branch diameter is one of the most important factors influencing the pruning torque requirements for all tested cultivars. The statistical tests (0.05 significance) revealed that the pruning torque varies significantly for different branch diameters ranging from 6 to 20 mm. It was found that the cutting torque required for the ‘Honeycrisp’ branches was significantly lower than that for ‘Gala’, ‘Fuji’, and ‘Golden Delicious’ branches. ‘Gala’ branches had the highest torque requirements. To cut branches of ‘Fuji’ trees, the required cutting torque for branches placed at the cutter center was higher compared with the cutter pivot. The statistical tests indicated that the difference in required cutting torques for both branch-blade contact points was significant (0.05 level of significance). The cutting torque requirement for a 30° angle (bevel) cut was higher compared with a 0° (straight) cut for ‘Fuji’ apple trees, but the statistical analysis suggested that the difference was insignificant at a level of significance of 0.05. Comparing all test results (four cultivars and cutting settings), the highest cutting torque of 6.98 N·m was observed for ‘Fuji’ branches with a diameter of 20 mm for a straight cut with the branch placed at the shear cutter center. Therefore, it is suggested that the robotic pruner should provide a comparable torque for successful cutting. The outcomes of this study are important for the selection of appropriate cutting mechanisms for the future development of a robotic pruning system.

In the United States, the apple (*Malus × domestica*) industry contributes ≈\$2.75 billion to the economy (U.S. Department of Agriculture, 2020). Pruning is an important cultivation technique that impacts the fruit quality and usefulness of disease control practices (Glenn and Campostrini, 2011). Manual pruning of apple trees is one of the most labor-intensive operations, requiring ≈80 to 120 h·ha⁻¹ of labor (Mika et al., 2016) and accounting for 20% of the total labor costs (Crassweller et al., 2020). To deal with decreasing labor availability and higher associated costs, alternate solutions are needed. A few studies have reported mechanical pruning or hedging of tree fruits (Krueger et al., 2013), but these operations are less useful for apple trees (He and Schupp, 2018; Zahid et al., 2021a) because they can result in unwanted vegetative growth.

Robotic pruning is a selective branch operation that can produce

accurate cuts using an end-effector tool attached to the robotic arm (Lehnert, 2012). A few studies have reported the development of pruning robots for different crops such as apple (Zahid et al., 2020a, b), grape [*Vitis vinifera* (Botterill et al., 2017)], and cherry [*Prunus avium* (You et al., 2020)]. Robotic pruning of apple trees is a challenging task because the crowded and overlapped branches result in narrow spaces for maneuvering the robot inside the canopy (He and Schupp, 2018; Zahid et al., 2021b). Therefore, the design considerations for a pruning robot should

include the maneuverability and spatial requirements during manipulation. The end-effector is an integral component of a robotic pruning system equipped with a cutting tool operated by an appropriate mechanism to perform the cutting action (Zahid et al., 2021a). Researchers have developed pruning end-effectors using different cutting mechanisms, such as a saw disc (Botterill et al., 2017) and shear blades (Zahid et al., 2020b). For robotic pruning, the shear blades were more successful than a saw disc and delivered smooth cuts (Zahid et al., 2020b) essential for tree pruning to avoid negatively affecting the healing process. A compact robotic cutter is essential for successful operation (Zahid et al., 2021b), which requires the selection of appropriate cutter system components. However, a prerequisite for component selection is to determine the force (torque) required to cut the branches.

The dynamic analysis of branch cutting is the first step in developing an effective robotic pruning system. In recent years, there have been dynamic analyses of robotic operations for various specialty crops, such as harvesting apples (Davidson et al., 2016), olives [*Olea europaea* (Ruiz et al., 2018)], tomatoes [*Solanum lycopersicum* (Li et al., 2019)], and button mushrooms [*Agaricus bisporus* (Huang et al., 2021)]. A few studies also reported torque requirements for branch cutting. Branch diameter is one of the most important factors affecting the cutting torque. Pezzi et al. (2009) evaluated the branch cutting force requirements for pruning grapevines and reported that the forces required for pruning vary with vine diameter, cultivar, and pruning time of year. Zahid et al. (2020a) estimated the torque required to prune ‘Fuji’ apple tree branches, but the tests were conducted in the laboratory; therefore, the results may not truly represent the force required to cut the branches in field conditions. The tests were conducted on ‘Fuji’ apple trees, but the cutting

Units

To convert U.S. to SI, multiply by	U.S. unit	SI unit	To convert SI to U.S., multiply by
0.4047	acre(s)	ha	2.4711
25.4	inch(es)	mm	0.0394
0.4536	lb	kg	2.2046
4.4482	lbf	N	0.2248
1.3558	lbf ft	N·m	0.7376

torque requirements for different cultivars may vary because of variations in specific wood densities.

The cutting angle of the end-effector is critical for robotic pruning operation. Ideally, the cutter should reach the target branches perpendicular to limb orientation (straight cut); however, the straight cut may not always be possible because of the narrow workspace. Criss-crossed branches limit the robot's ability to attain a desired approach angle, which may require different approach angles of the cutter to target specific branches, possibly resulting in bevel (inclined) cuts (Zahid et al., 2021b). The effective cut size (surface area) of the inclined (bevel) cut is greater than the straight cut when cutting a branch at the same point; thus, the required cutting torque could be different and needs to be investigated.

The positioning of a branch on the blade before cutting (branch-blade contact point) is also crucial for determining the robot kinematics to accurately reach the target cut points. The robot kinematics are calculated based on three-dimensional (3D) coordinate frames. Selecting the origin of the cutter coordinate frame is a key factor that could affect the positioning of the robot. This is particularly important when the branches are pruned near the tree trunk: the cutter may collide with the trunk or fail to attain the desired

cutting angle at a defined reference point such as at the cutter pivot or cutter center. Thus, the cutter may need to use a different reference point based on the canopy requirements and to reduce potential collisions with the tree trunk. However, the variations in the branch-blade contact points could also affect the torque required to cut the branches. Therefore, this should be investigated to understand the accurate robot kinematics during pruning.

Considering the knowledge gaps, the primary goal of this study was to determine the branch-cutting torque requirements for 'Fuji', 'Gala', 'Honeycrisp', and 'Golden Delicious' trees under different cutting settings to assist the development of an automated pruning system. The variations in the cutting settings could alter the cutting torque requirements, thus affecting the performance of a robotic pruning system. Thus, our study was performed with objectives: 1) to integrate force measurement and inertial measurement unit (IMU) sensors with a manual shear pruner to perform pruning dynamic tests; 2) to investigate pruning torque requirements for different apple cultivars; and 3) to determine the effects of branch placement on the cutter (contact point) and cutting angle on torque requirements.

Materials and methods

SENSORS SELECTION AND CALIBRATION. The selection of an appropriate force measurement sensor was critical for the pruning torque measurement tests. The key selection criteria were the saturation level (maximum measurable force) and the compactness of the sensor to facilitate integration. In a recent study, Zahid et al. (2020a) used a flexible force sensor (FlexiForce 1131_0; Tekscan, Boston, MA) with a maximum force limit of 20 N, but the sensor reached the maximum limit when cutting 16-mm-diameter 'Fuji' apple branches. Thus, a thin film resistive force/load cell sensor (FlexiForce 3101_0, Tekscan) was used to measure the branch-cutting force. The sensor can be loaded with up to 11.5 kg, and with a response time of 5 μ s, the maximum measurable force is 111 N with a repeatability error of 2.5%. The sensor was calibrated to convert the electrical output (millivolts) to force unit (Newtons) following the

guidelines provided in the user manual. For calibration, the sensor was loaded with standard known weights ranging from 0.1 to 3.5 kg using a 3D printed loading/calibration stand to distribute the load/weight evenly across the sensing area (Fig. 1A). The sensor was placed under the calibration stand and the load/weight was applied (incremental loading) by putting the weights on top. The sensor was integrated with a multisensor interface kit (InterfaceKit 8/8/8_1018_2B; Phidgets, Calgary, AB, Canada) to record the sensor output corresponding to each applied load/weight. For the calibration, 23 data points were used (20 points between 0.1 and 2.0 kg with 0.1-kg increments and 3 points from 2.0 to 3.5 kg with 0.5-kg increments). The process was repeated three times for each load/weight (data point), and the average sensor output was used to develop the model. Figure 1B shows the model curve developed to measure the force corresponding to sensor values using the Curve Fitting Toolbox of MATLAB programming software (version 2021a; MathWorks, Natick, MA). The lower and upper prediction bounds with 95% prediction intervals were also added to indicate the chance of the cutting force to be contained within these bounds. The model Eq. [1], with an R^2 of 0.99 and root mean square error of 0.396 N, was developed to calculate the applied force from the sensor readings:

$$F = 14.76 - 13.95 \times \cos(S \times 0.002958) + 20.31 \times \sin(S \times 0.002958) \quad [1]$$

where F is the force in Newtons and S is millivolts. An IMU sensor (Spatial Precision 3/3/3_1044_1B; Phidgets) was used to measure the cutter placement angle. The IMU sensor has a three-axis gyroscope with the maximum speed of $\pm 100^\circ/\text{s}$ at a resolution of $0.003^\circ/\text{s}$.

SENSORS INTEGRATION AND DATA ACQUISITION. The force and IMU sensors were integrated with a manual shear pruner (Fig. 2). A shear pruner consisting of a cutting blade and an anvil (Extendable Anvil Lopper; Gardtech, Ningbo, China) was used, and the sensor was attached to handle of the blade part. A 3D printed hand tool was used to apply force directly to the sensor. The force sensor was attached

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Fig. 1. (A) Force sensor calibration setup. (B) Force sensor calibration model developed to convert the sensor reading to force unit (Newtons) for apple branch pruning analysis; 1 N = 0.2248 lbf.

to the arm of the loppers in a way that its sensing part was positioned on the top of the handle to coincide with the point of contact of the operator. The distance between the sensor and cutter pivot was measured as 600 mm, and the applied cutting torque was calculated using Eq. [2]. The IMU sensor was attached at the top of the shear blade to measure the cutting angle. The origin of the IMU sensor was set as in line with the cutter pivot point.

$$\begin{aligned} \text{torque } (T) &= \text{force } (F) \\ &\times \text{sensor distance } (D) \end{aligned} \quad [2]$$

where T is the torque required to cut the branches in Newton meters, D is the distance between the sensor and the cutter pivot in meters, and F is the applied cutting force measured in Newtons. Both sensors were attached to a laptop computer with a pre-installed operating system (Windows 10; Microsoft Corp., Redmond, WA). The data for the force sensor were recorded using data-logging software (FlowBotics Studio; RobotShop, Mirabel, QC, Canada), and the data for the IMU sensor were recorded with data-logging and visualization

software (Control Panel, Phidgets). The data files for the force measurements were saved in .txt format and contained the sensor response values for each applied cut, which were further converted to torque using Eq. [1]. For the force measurements, the time interval for data logging was set to 0.05 s. Because the data were logged with a small time resolution, multiple data points were recorded for each cut. The peak sensor values were used to calculate the applied torque for each cut, and a vernier caliper was used to measure the diameter of the branches. The diameters were converted to integers based on the fractional value. For example, if the fractional value was more than 0.5, then the diameter was recorded as the next integer. For the IMU sensor, the graphical user interface was used to monitor the cutter angle, and the cuts were made at the desired angle.

FIELD TESTS. The field tests were conducted at the Penn State Fruit Research and Extension Center in Biglerville, PA, using ‘Gala’, ‘Fuji’, ‘Honeycrisp’, and ‘Golden Delicious’ trees (Fig. 3). The ‘Gala’, ‘Honeycrisp’, and ‘Golden Delicious’ trees were planted in 2005, and the ‘Fuji’ trees were planted in 2009. The ‘Gala’, ‘Honeycrisp’, and ‘Fuji’ trees were grown on ‘M.9’ NAKB T337 rootstock, and the ‘Golden Delicious’ trees were grown on ‘Budagovsky 9’ rootstock. These trees were trained into tall spindle architecture. The tests were conducted during the dormant pruning season in February. A total of 630 cuts were made. The number of branches selected from each tree was conditional to the branches available to cut, and approximately similar numbers of branches were selected from each tree. The diameter range for the tests was selected based on the size of the branches available in all selected orchards (visual observations before the tests).

Test one investigated the pruning torque requirements for different apple cultivars. From each cultivar, 15 apple trees were selected randomly, and a total of 105 cuts were made on branches with diameters ranging from 6 to 20 mm (seven cuts for each diameter size). The cutting angle was set as “perpendicular to the limb” (straight cut), and the branch-blade contact point was set as the “pivot cut.” The

Fig. 2. A force measurement and inertial measurement unit sensors system integrated to a manual shear pruner for branch cutting dynamic test of different apple cultivars with different cutting settings.

pivot cut is defined as a fully opened cutter and the branch as close as possible to the pivot point of the shear blades (Fig. 3).

Test two investigated the effects of different branch-blade contact points on cutting torque requirements (Fig. 4A). For this test, 10 ‘Fuji’ apple trees were selected, and a total of 105 cuts were made on branches ranging

from 6 to 20 mm (seven cuts for each diameter size) with a branch-blade contact point set as the cutter center. For comparison, the cutting torque data from the pivot cut for ‘Fuji’ apple tree branches were taken from the dataset of test one.

Test three investigated the effects of different cut angles on the pruning torque requirements (Fig. 4B). The

test was conducted using ‘Fuji’ apple trees (105 cuts were made on 10 randomly selected trees) with branches ranging from 6 to 20 mm (seven cuts for each diameter size). The cutting angle was set as 30° relative to the normal (bevel cut). For comparison, the cutting torque data for the straight cut were taken from the test one dataset.

STATISTICAL ANALYSIS. The data analysis was performed using statistical software (Minitab v18; Minitab, State College, PA). Because the data consisted of one categorical variable (cultivars) and one metric interval variable (branch diameter), a general linear model was fitted to perform the analysis of covariance (ANCOVA) test to determine the significance in torque requirements between different cultivars. The ANCOVA test was selected to remove the impact of branch diameter on the response variable and to increase the sensitivity of the test for categorical variable. For the analysis, the cutting torque was the response variable, the cultivar was the categorical variable, and the branch diameter was the covariate (to reduce the error sum of squares). Separate ANCOVA tests were performed to investigate the significance between the cutting angles (0° vs. 30° angles) and branch blade contact points (pivot cut vs. center cut). Finally, a post hoc Tukey’s test (95% confidence) was performed for pairwise comparison/grouping to investigate the significance between different means. Tukey’s test was performed to determine which group differs from the others in all possible pairwise comparisons of means.

Results

EFFECT OF CULTIVAR ON PRUNING TORQUE REQUIREMENTS. The torque requirements for cutting the branches of four different cultivars are shown in Fig. 5. The results suggested that the ‘Gala’ tree branches required the highest cutting torque, whereas the ‘Honeycrisp’ tree branches required the lowest torque. Different regression models were tested using the MATLAB curve fitting toolbox. As shown in Fig. 5, the pruning torque required for all four tested cultivars follows a quadratic relationship (second order polynomial). The data points for ‘Fuji’ tree branches at 12

Fig. 3. (A) Field tests for branch pruning torque measurements using a manual shear pruner. (B) Pruning cuts at different blade cutting points (center cut vs. pivot cut) in ‘Fuji’ apple trees. (C) Pruning cuts at different cutting angles (0° and 30° angles relative to the normal) in ‘Fuji’ apple trees.

Fig. 4. (A) An illustration of different cutting points (branch placed at the cutter center and cutter pivot) to investigate the effect of cutting points on pruning torque requirement in 'Fuji' apple trees with straight cut. (B) An illustration of different cutting angles (0° and 30° angles relative to the normal) to investigate to effect of cutting angles on pruning torque requirements (straight vs. bevel cut).

and 13 mm deviated from the trend in the data, and this variation could be caused by an error in the diameter measurements corresponding to the cut.

Table 1 presents the results of the statistical analysis performed to test

the significance of cutting torque requirements for different cultivars. The null hypothesis was that the mean torque required for branch cutting was equal for different cultivars. The ANCOVA test was performed to

test the hypotheses at a level of significance of 0.05. The P values for branch diameter and cultivars were calculated as <0.001 , which was lower than the level of significance (0.05). Thus, the null hypothesis was rejected in favor of the alternate hypothesis, which suggested that the amount of cutting torque for different cultivars varies significantly. The R^2 calculated from the general linear model was 84.15%.

Tukey's test was performed for paired comparisons and grouping to test the significance between cultivars (Table 2). Tukey's test grouping results showed that the 'Gala' and 'Golden Delicious' share the same group "a" and 'Golden Delicious' and 'Fuji' share same group "b," which indicated that the cutting torque for 'Golden Delicious' was not significantly different from that of the other two cultivars, whereas a significant difference was found between 'Gala' and 'Fuji'. However, the grouping showed the cutting torque requirements for 'Gala' and 'Fuji' tree branches varied significantly. The 'Honeycrisp' was assigned group "c," indicating that the cutting torque was significantly different from all other tested cultivars, which is caused by the difference in the specific wood density. The regression equations are listed in Table 2. The highest R^2 of 99.21% was measured for 'Golden

Fig. 5. Cutting torque requirements for pruning different apple cultivars (Gala, Fuji, Honeycrisp, and Golden Delicious) for branches ranging from 6 to 20 mm with straight cut and branches placed at cutter pivot. See Table 2 for the equations for the fitted curves; 1 N·m = 0.7376 lbf ft, 1 mm = 0.0394 inches.

Table 1. Test 1: Results of analysis of covariance test performed in statistical analysis software for cutting torque requirements of different apple cultivars (Gala, Golden Delicious, Fuji, and Honeycrisp) for branches ranging from 6 to 20 mm (0.24–0.79 inches) with cutter orientation perpendicular to the branch (straight cut).

Source	<i>F</i>	<i>P</i>	Significance ^z
Branch diameter	1885.77	<0.001	**
Cultivars	69.44	<0.001	**

^zSignificance level = 0.05; ** significant.

Delicious' apple trees. The lowest R^2 of 97.63% was measured for 'Fuji' apple trees.

EFFECT OF THE BRANCH-BLADE CONTACT ON PRUNING TORQUE REQUIREMENTS. The effect of the branch-blade contact point on pruning torque requirements for 'Fuji' branches is shown in Fig. 6. The data from the field tests indicated that a higher cutting torque was required when the branch was placed at the cutter center compared with near the pivot point of the cutter. For both contact points, the cutting torque required for smaller diameter branches (up to 9 mm) was not considerably different. As the diameter of the branches increased, the difference in the applied cutting torque increased, with the center cut requiring higher torque to cut the branches.

A statistical analysis to test the significance of cutting torque for different branch-blade contact points of 'Fuji' apple was performed (Table 3). The null hypothesis was that the required mean torque for branch cutting was equal for different branch-blade contact points with varying branch diameters. The ANCOVA test was performed to assess the hypothesis at a level of significance of 0.05. The *P* values for branch diameters and branch-blade contacts were calculated

as <0.001 and 0.007, respectively. Because both *P* values were less than the set significance level (0.05), there was enough evidence to reject the null hypothesis in favor of the alternate hypothesis, which suggested that the mean values of the cutting torque were significantly different.

Tukey's test was also performed for grouping to test the significance between different cutting points (Table 4). Tukey's test grouping showed that the center cut and pivot cut were assigned different groups, "a" and "b," respectively, which suggested that the mean torque requirement was significantly different. A regression model for the center cut torque requirements using a second-order polynomial and an R^2 of 98.29% was determined (Table 4). The regression model for the pivot cut torque requirements for 'Fuji' branches was calculated in the previous section.

EFFECT OF THE CUTTING ANGLE ON PRUNING TORQUE REQUIREMENTS. The effect of cutting angles on torque requirement for 'Fuji' apple trees is shown in Fig. 6. The results suggested that the cutting torque requirements for 'Fuji' tree branches varied with the change in the angle of the cut. The cutting torque required for pruning branches at the 30° bevel cut was

considerably higher compared with the 0° straight cut. This is also explained by the fact that a bevel cut requires the blades to go through more material compared with a straight cut. The effect of varying cutting angles on torque requirements for pruning 'Fuji' branches was statistically investigated. The null hypothesis was that the mean cutting torque for branch cutting was equal for different cutting angles with varying branch diameters. Table 5 presents the result of the ANCOVA test performed to test the hypothesis at a level of significance of 0.05. The *P* values for branch diameter and cutting angles were calculated as <0.001 and 0.06, respectively. Because the set significance level (0.05) was less than the *P* value for branch diameters, the first null hypothesis was rejected to accept the alternate hypothesis, indicating that a significant difference in the torque requirements for different diameter branches exists. As the second hypothesis, because the *P* value was higher than the set level of significance (0.05), the null hypothesis could not be rejected. This shows that the difference in cutting torque for different cutting angles was insignificant.

Tukey's test was performed for paired comparisons and grouping of required torque at different cutting angles (Table 6). The Tukey's test assigned group "a" to both test factors, 30° and 0°, which suggested that the difference between the mean torques was insignificant. A regression model with a second-order polynomial and R^2 of 0.9733 was developed for the 30° cutting angle dataset of 'Fuji' branches (Table 6). The regression model of the 'Fuji' tree at a 0° cutting angle is developed in the previous section.

Table 2. Test 1: Results of grouping using Tukey's test and statistical analysis software for cutting torque requirements of different apple cultivars (Gala, Golden Delicious, Fuji, and Honeycrisp) for branches ranging from 6 to 20 mm with the cutter orientation perpendicular to the branch (straight cut).

Cultivar	Sample size	Mean torque (N·m) ^z
Gala	105	2.70 a ^y
Golden Delicious	105	2.66 ab
Fuji	105	2.45 b
Honeycrisp	105	1.54 c
Regression equations ^z		
Fuji	Torque (N·m) = 0.09 × diameter ² − 0.51 × diameter (mm) + 1.13	R ² = 97.63%
Gala	Torque (N·m) = 0.07 × diameter ² + 0.04 × diameter (mm) − 0.92	R ² = 99.19%
Golden Delicious	Torque (N·m) = 0.07 × diameter ² + 0.04 × diameter (mm) − 0.65	R ² = 99.21%
Honeycrisp	Torque (N·m) = 0.09 × diameter ² − 1.20 × diameter (mm) + 6.08	R ² = 98.35%

^z1 N·m = 0.7376 lbf ft, 1 mm = 0.0394 inches.

^yTukey's test grouping at 95% confidence. Means that do not share the same letter are significantly different.

Fig. 6. Cutting torque requirement for pruning ‘Fuji’ apple branches at different blade cutting points (center cut vs. pivot cut as control) and at different cutting angles (0° as control vs. 30° bevel cut) for branches ranging from 6 to 20 mm with straight cut. See Tables 4 and 6 for equations for the fitted curves; 1 N·m = 0.7376 lbf ft, 1 mm = 0.0394 inches.

IMPLICATIONS OF THE STUDY FOR DESIGNING ROBOTIC PRUNERS. The cutting torque required to prune branches for different apple cultivars is one of the most important criteria required by designers for the selection of appropriate automated pruning system components (Zahid et al., 2021b). The key design benchmarks for apple pruning robots include an efficient cutting mechanism with fewer spatial requirements (He and Schupp, 2018). The branch pruning dynamic analysis conducted in this study could guide the development of a robotic apple tree pruning system. Our results can assist the robotic system designers with the selection of the appropriate components to develop the cutting mechanism of the pruning end-effector. As the results indicated, ‘Gala’ required the highest pruning torque compared with ‘Fuji’, ‘Golden Delicious’, and

‘Honeycrisp’. Based on the four cultivars evaluated, designers could consider the torque requirements of ‘Gala’ as a reference for developing the pruning end-effector.

The successful robotic pruning operation also requires effective path planning to reach the target cut point on the selected branches. For path planning, two important factors are the position of the cutter coordinate frame and the approach to the target branch. The cutter coordinate frame (x-axis, y-axis, and z-axis) defines the origin of the cutter, and it is used by the path planning algorithms to reach the targeted cut point. Because the required torques were significantly different for the two branch-blade contact points, it is implied that the origin of the cutter frame should be selected based on the available torque of the robotic pruning system. Because

the measured cutting torque was less when the branch was located nearest to the cutter pivot, the ideal case could include defining the cutter coordinate frame centered at the pivot of the cutter.

The pruning cut angle affects the required cutting torque as well as the spatial requirements for robotic tree pruning. The approaching angle refers to the final position of the robot at the target branch to produce the desired angle cut (bevel or straight cut). Because the cut angle does not influence the branch regrowth, the cutter could reach the target point using different cutting positions to cut the branches. Because apple trees have a complex canopy structure, the path-planning scheme has to estimate the robot position by avoiding obstacle branches (Zahid et al., 2021b). However, when the position changes from a straight cut to a bevel cut, the effective cut size (cross-sectional area) becomes larger, requiring higher cutting torque. For the ‘Fuji’ trees, the results indicated that the cutting torque required for 30° bevel cuts was larger compared with that of the straight cuts (0° cut), but the difference was insignificant at a 0.05 significance level. However, because of the complex apple tree canopy, the robot may have to attain a different cutting

Table 3. Test 2: Results of an analysis of covariance performed using statistical analysis software for cutting torque requirements of different branch-blade cutting points (pivot cut and center cut) of ‘Fuji’ apple tree branches ranging from 6 to 20 mm (0.24–0.79 inches) with the cutter orientation perpendicular to the branch (straight cut).

Source	F	P	Significance ^z
Branch diameter	1555.51	<0.001	**
Cutting points	7.46	0.007	**

^zSignificance level = 0.05; ** significant.

Table 4. Test 2: Results of grouping using Tukey’s test and statistical analysis software for cutting torque requirements of different branch–blade cutting points (pivot cut and center cut) of ‘Fuji’ apple tree branches ranging from 6 to 20 mm with the cutter orientation perpendicular to the branch (straight cut).

Contact point	Sample size	Mean torque (N·m) ^z
Center cut	105	2.65 a ^y
Pivot cut (control)	105	2.42 b
Regression equations ^z		
Center cut	torque (N·m) = 0.09 × diameter ² – 0.18 × diameter (mm) – 0.48	R ² = 98.29%
Pivot cut (control)	torque (N·m) = 0.09 × diameter ² – 0.51 × diameter (mm) + 1.13	R ² = 97.63%

^z1 N·m = 0.7376 lbf ft, 1 mm = 0.0394 inches.

^yTukey’s test grouping at 95% confidence. Means that do not share the same letter are significantly different.

posture (higher than 30° cut), which could result in higher cutting torque requirements. Thus, it is essential to estimate the torque at different cutting angles, and the highest cutting torque should be used as a guide for developing the robotic cutting mechanism. In the future, experiments to investigate the effect of different cutting angle on pruning torque requirements for different apple cultivars will be conducted.

During the tests, it was observed that the applied cutting torque depends on the position (location) of the selected branch of the tree. For example, the cutting torques applied for branches in the upper canopy of the tree and the lower canopy could be more strenuous because of the working posture of a human operator. However, for our experiments, we selected from each section (top, middle, and bottom) of the tree. To reduce the variability in the measurements, only branches that were convenient to cut were selected for cutting. The pruning cuts were applied at different locations on the selected branches, including the middle of the branches and close to the origination point of each branch. It was observed that when the cut was made close to the trunk (origination point), the reachability of the cutter was reduced. For example, when cutting some of the branches at the origination point, the cutter was not able to attain the cutting position for a straight cut

because the cutter hit the trunk; additionally, for some of the branches, the cutter failed to attain the position for a 30° angle (bevel) cut. A similar challenge was observed with the branch–blade contact point (center or pivot cut). The cutter reachability was greatly affected by the branch angle (too large/small), diameter, and blade size. Further investigations are required to develop a mathematical model for estimating the minimum distance (closest) from which the shear cutter could reach the origination point of a branch having a certain angle and diameter. The robotic pruner could use this information to automatically select the final position of the cutter and location (distance) of the pruning cut on the selected branch.

Our analysis of branch pruning provides the preliminary guidelines for designing the cutting mechanism of an end-effector for robotic apple tree pruning. Because the maximum component sizes are limited because of the complex tree canopy, this analysis is particularly important to design assessments that will determine what size motors or actuators will be required or whether a mechanical advantage will be required to supply the required cutting torque. The selection of larger components because of an overestimation of the cutting torque could lead to expanded spatial requirements, possibly negatively affecting the robotic pruning operation. In addition, to estimate the maximum

cutting capabilities of the pruning robot, cutting torque information for branch pruning is required. The cutting torque requirement for different cultivars could also be affected by other factors such as branch position within the canopy and tree and branch age. However, these factors were not considered during the tests. In the future, tests will be conducted to investigate the effect of these factors on cutting torque requirements for different apple cultivars. Because the specific wood density varies between cultivar and species, the results of our study are valid for pruning apple trees (selected cultivars). The cutting torque requirements for other trees/shrubs could possibly vary; therefore, additional tests will be required.

Conclusions

A sensor system was developed to investigate the torque required for pruning branches of different apple cultivars. Force and angle measuring sensors were integrated with a manual pruner, and field tests were conducted. The cutting torque required to prune branches of different apple cultivars varies significantly. To develop an end-effector with sufficient cutting capabilities, the selection of components for the cutting mechanism should consider the cutting torque requirements of the target cultivar for efficient robotic pruning operations. The branch–blade contact points significantly affected the torque required to cut the branches for the ‘Fuji’ apple trees. This factor should be considered for defining the end-effector coordinate frame during the path planning of a robot to reach the target. Because the cutter pivot resulted in lower torque requirements, the coordinate frame should be defined at the pivot point of the blades. For ‘Fuji’ apple trees, the bevel cut at a 30° angle increased the cutting torque requirements compared with the straight cut,

Table 5. Test 3: Results of an analysis of covariance performed using statistical analysis software for cutting torque requirements of different cutting angles (0° and 30°) of ‘Fuji’ apple tree branches ranging from 6 to 20 mm (0.24–0.79 inches) with the cutter angle at 30° relative to the normal cut (bevel cut) and straight cut as the control.

Source	F	P	Significance ^z
Diameter	1308.00	<0.001	**
Cutting angles	3.58	0.06	NS

^zSignificance level = 0.05; ** significant; NS, not significant.

Table 6. Test 3: Results of grouping using Tukey's test and statistical analysis software for cutting torque requirements of different cutting angles (0° and 30°) of 'Fuji' apple tree branches ranging from 6 to 20 mm with the cutter angle at 30° relative to the normal cut (bevel cut) and straight cut as the control.

Cutting angle	Sample size	Mean torque (N·m) ^z
30° bevel cut	105	2.55 a ^y
0° straight cut (control)	105	2.38 a
Regression equations ^z		
30° bevel cut	torque (N·m) = 0.09 × diameter ² – 0.19 × diameter (mm) – 0.16	R ² = 97.33%
0° straight cut (control)	torque (N·m) = 0.09 × diameter ² – 0.51 × diameter (mm) + 1.13	R ² = 97.63%

^z1 N·m = 0.7376 lbf ft, 1 mm = 0.0394 inches.

^yTukey's test grouping at 95% confidence. Means that do not share the same letter are significantly different.

but the effect was found to be statistically insignificant. A cut with a larger angle could have larger torque requirements; however, this needs to be investigated. The results of this study are important for the development of a cutting mechanism for robotic pruning of apple trees. The branch diameter, position, and age are also important parameters that could influence the cutting torque, which will be investigated in future studies. Additionally, different cutting angles and cut points will be studied for different apple cultivars.

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