2950 Niles Road, St. Joseph, MI 49085-9659, USA
269.429.0300 fax 269.429.3852 hq@asabe.org www.asabe.org

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Evaluation of Branch Cutting Torque Requirements Intended for Robotic Apple Tree Pruning

Azlan Zahid, Md Sultan Mahmud, Long He*
Department of Agricultural and Biological Engineering, Pennsylvania State University, University Park, PA 16802, USA

Penn State Fruit Research and Extension Center (FREC), Biglerville, PA 17307, USA

***** Correspondence: luh378@psu.edu***

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ABSTRACT. *Robotic pruning is a potential solution to address the issue of labor shortages, but it has certain design challenges. The torque required for cutting branches is an important parameter for designing a pruning end-effector. In this study, branch cutting torque and angle were investigated with envisioning the development of robotic end-effector. The experimental system comprised of a manual shear pruner with a force measurement sensor, capable of detecting the forces exerted by the hand. Besides, an Inertial Measurement Unit (IMU) was also used to record the orientation of the shear blade. A series of field tests were conducted on four apple cultivars (Fuji, Gala, Honeycrisp, and Golden Delicious), and the cutting torque was calculated for different diameter branches. The Statistical analysis suggested that the torque required for pruning Honeycrisp is significantly lower than that for Gala, Fuji, and Golden Delicious. The paired comparison between Golden Delicious with Gala and Fuji suggested that the cutting torque variations were non-significant. The Gala has the highest torque requirements while the lowest torque requirements was observed for Honeycrisp. The results also indicated that no significant difference in required cutting torque was found among the different cutting angles for Fuji apple trees. While, the branch-blade contact point significantly affects the torque required for cutting branches of Fuji apple trees. The required cutting torque was higher for branches placed at cutter center compared to cutter pivot. The outcomes of the study are vital to select appropriate cutting mechanism for the future development of automated pruning system.*

Keywords. *Apple (Malus x domestica Borkh.), automated pruning, branch cutting, pruning dynamics, pruning end-effector.*

1. Introduction

Apple is one the most valued tree fruit crops in the U.S., contributing about $2.75 billion to the economy (NASS-USDA, 2020). Automation have been widely applied in the agricultural environment, resulting in significant increase in production efficiency, but the production operations of tree fruits are still depending on manual labor. In an apple orchard, year around labor is required to perform various operations such as pruning, thinning, and harvesting. Pruning is an important cultivation technique, effects the fruit quality and usefulness of disease control practices (Glenn & Campostrini, 2011). Manual pruning of apple trees is one of the most labor intensive operations, requires about 80-120 working hours of labor per hectare (Mika et al., 2016), accounting for 20% of the total labor costs (Crassweller et al., 2020). Due to decreasing labor availability and associated costs, these traditional pruning methods put down issues to the sustainability of the apple industry. A few studies have been reported on mechanical pruning or hedging of tree fruits (Krueger et al., 2013), but these operations are not as much of useful for apple trees, due to non-selective branch cutting approach (He and Schupp, 2018). To address these issues, the research has been focused on robotic pruning.

Robotic pruning is a selective branch operation, which can produce accurate cuts using an end-effector tool attached to the robotic arm (Lehnert, 2012). Researchers have worked on adoption of robotics, mainly for the harvesting fruits and vegetables such as apple (Silwal et al., 2017), citrus (Lu et al., 2018), sweet pepper (Bac et al., 2016), and cucumber (Bao et al., 2016). Studies have reported the development of robots for pruning grapevines having uniform canopy architecture (Botterill et al., 2017; Vision-Robotics Corporation, 2015), while a few studies reported for robotic pruning of trees having complex canopies such as apple (Zahid et al., 2020a) and cherry (You et al., 2020). The robotic pruning of apple trees is a challenging task due to the complexity of tree canopy. The crowded and overlapped branches, result in narrow spaces for maneuvering of the cutter inside the canopy (He and Schupp, 2018). Thus, the designing a pruning robot for apple trees require considerations of spatial requirements and maneuverability.

The end-effector is an integral component of a robotic pruning system, perform the cut on the targeted branches. The end-effector comprised of the cutting tool operated by an appropriate mechanism to perform the cutting action. The cutting mechanism is selected based on intended work (Kondo & Ting, 1998), could be operated using electrical, mechanical, pneumatic, or hydraulic power source. Researchers have developed pruning end-effectors with different cutting mechanism such as saw disc or rotating mill (Botterill et al., 2017) and shear blades (Zahid et al., 2020b). The shear pruner end-effectors produced smooth and separation cuts, essential for apple tree pruning to avoid negative affect on healing process. As mentioned earlier, the complex canopy of apple trees limits the maneuverability of the cutter; thus, a compact robotic cutter is essential for successful operation, require selection of appropriate size of system components. However, a prerequisite for size selection is it to determine the forces (torque) required to cut the branches of different diameter and cultivars.

The dynamic analysis for branch cutting is the first step in developing an effective robotic pruning system. In the recent years, the dynamic analysis intended for robotic operations on various specialty crop has been reported such as harvesting apples (Davidson et al., 2016), olives (Ruiz et al., 2018), tomatoes (Li et al., 2019), and mushroom picking (Huang et al., 2021). A few studies also reported on torque requirement for branch cutting. Pezzi et al. (2009) evaluated the branch cutting force requirements for pruning grapevines and reported that the forces required for pruning varies with vine variety, diameter, and pruning period. Zahid et al. (2020a) estimated the force required to prune Fuji apple tree branches, but the tests were conducted in the laboratory, establishing near-ideal cutting conditions, which may not truly represent the force required to cut the branches in the field conditions. Alongside, the cutting torque required for other cultivars were not calculated; however, the cutting torque requirements for different cultivars may varies due to variation in the specific densities.

The cutting angle of the end-effector is critical for robotic operation, adjusted by the approach poses of the robotic pruner at the target branches (Zahid et al., 2020c). The shear cutter should reach the target branches with a specific range of orientations. Ideally, the cutter should reach the target branches at perpendicular to limb orientation (straight cut); however, as the apple tree has a complex architecture, makes robotic pruner difficult to maneuver. In that perspective, the crisscross branches limit the robot ability to attain desired cutting posture. The robot may require additional approach poses of the cutter at target branches, results in producing bevel (inclined) cuts. The selection of alternate approach poses of the robot could be achieved using collision-free path planning algorithms by sensing the surroundings of the target branch. While, cutting a branch at same point, the effective cut size (surface area) of the inclined cut is greater than the size of the straight cut, the required cutting torque could be different and needs to be investigated.

The positioning of the branch on the shear blade (branch-blade contact point) is also crucial for determining the robot kinematics and efficient path planning to accurately reach the target cut points. The robot kinematics are calculated based on the three-dimensional (3D) coordinate frames, the selection of origin of the shear cutter coordinate frame is the key factor that could affect the reachability of the robot. This is particularly important as the branches are pruned near the tree trunk, the cutter may collide with the trunk or fail to attain the desired cutting posture at a defined origin such as at cutter pivot or cutter center. Thus, the cutter may need to have a different origin frame based on the canopy requirements, to reduce the collision potential of the cutter with the tree trunk. However, the variation in the branch-blade contact points could also have an effect on the torque required to cut the branches, thus should be investigated to facilitate the accurate robot kinematics for effective robotic pruning operation. To address these questions, a comprehensive dynamic analysis for branch pruning is required envisioning the development of robotic pruning system for apple trees.

Considering the aforementioned knowledge gap, this study was conducted with the primary goal to investigate the branch cutting torque requirements for different apple cultivars (Fuji, Gala, Honeycrisp, and Golden Delicious). The force measurement and IMU sensor was integrated with the shear pruner to perform the experiment. Statistical analysis was performed to determine the interaction between different cultivars for pruning torque requirements. Alongside, the effect of branch placement (cut point) on the cutter and branch cutting angle on torque requirements were also investigated.

2. Materials and Methods

2.1 Sensors Selection and Calibration

Selection of an appropriate force sensor was critical for pruning torque measurement. It is critical to consider the saturation level (maximum measurable force) and the compactness of the sensor to facilitate integration. Zahid et al. (2020a) reported that using a thin film flexible force sensor (1131_0, Tekscan, Mass., USA) with a maximum measurable force limit of 20 N was not sufficient for cutting Fuji tree branches over 16 mm in diameter. Thus, a thin film resistive force/load cell sensor (FlexiForce 3101_0, Tekscan, Mass., USA) was used to measure the branch cutting torque in this study. The sensor could be loaded with up to 11.5 kg, and maximum measurable force was 111 N. The sensor was calibrated by loading the standard weights ranging from 0.1 kg to 3.5 kg using a 3D printed loading/calibration stand (Figure 1. (a)). For calibration, the sensor was collected to a laptop with Phideget InterfaceKit 8/8/8 interface (1018_2B, Phidgets, Calgary, Canada). The sensor was placed on the calibration stand, then the load/weight was applied (incremental loading) by putting the weights on top of it, and at the end the corresponding sensor values were recorded. Figure 1. (b) shows the Fourier model developed to measure the force corresponding to sensor values using Matlab (2021a, MathWorks, Mass., USA) Curve Fitting Toolbox. The developed Fourier model has an R-square of 0.9982, and RMSE as 0.396 N (40 gf). The following equation was developed to calculate the applied force using sensor value:

$$F = m * g = 14.76 - 13.95 * \cos(x * 0.002958) + 20.31 * \sin(x * 0.002958) * g \quad (1)$$

Where, F is the force in Newton, m is the mass corresponding to sensor value in kg, and g is the gravitational acceleration in m/s^2. To measure the cutting angle, a Phidget Spatial Precision 3/3/3_IMU sensor (1044_1B, High Resolution Phidgets, Calgary, Canada), was used. The spatial sensor has a 3-axis gyroscope with resolution of 0.07°/s and a maximum sampling speed of 4 ms per sample. The sensor was pre-calibrated; however, it was validated for accuracy with vertical and horizontal surfaces.

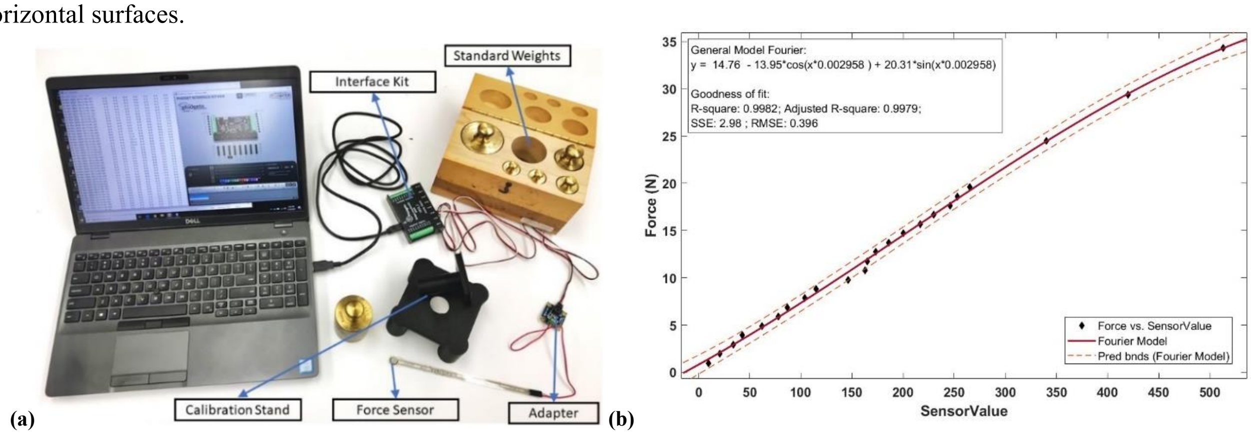

Fig. 1. (a) Force sensor calibration setup; (b) Force sensor calibration model.

2.2 Sensors Integration and Data Acquisition

The force sensor and IMU sensors were integrated to the manual shear pruner (Figure 2). As the sensing area of the force sensor was small (72 mm^2), a 3D printed hand tool was developed to apply force pointed directly on the sensor during the operation. The force sensor was attached to the arm of a 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 hand tool with the shear handles. The distance between the sensor and cutter pivot was set as 24 cm. A set of flexible cables were used to connect the force sensor to the adapter and analog port on the interface kit. The IMU sensor was attached at the top of the shear blade and the origin was set as in line with the cutter pivot point. The Eq. 2 was used to calculate the applied cutting torque.

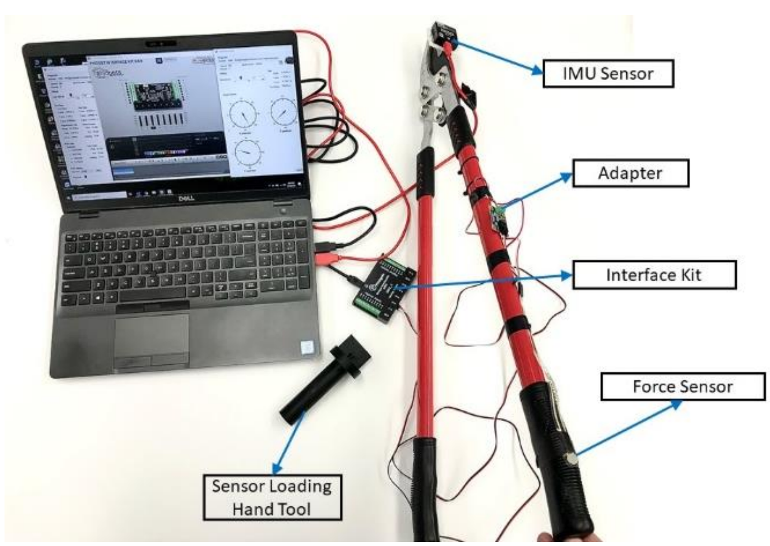

Fig. 2. Integrated sensors system with manual pruner

$$Torque\ (T) = Sensor\ Distance\ (D) * Force\ (F) \tag{2}$$

Where, T is the torque required to cut the branches in Nm; D is the distance between the sensor and the cutter pivot in m; F is the applied force in N. Figure 3 shows the flowchart for data acquisition and processing. Both integrated sensors were attached to a laptop computer system with Windows 10 operating system (Microsoft Inc., USA) and 16 GB memory. The sensors were connected to laptop computer using a USB Type A 3.0 port. The data for force sensor was recorded using the FlowRobotics Studio software (RobotShop Inc., Quebec, Canada) and the data for IMU sensor was recorded using Phidget Control Panel software (v1.6, Phidgets, Calgary, Canada). The recorded data log files were saved for analysis in Matlab and Minitab software (v18, Minitab, llc, PA, USA).

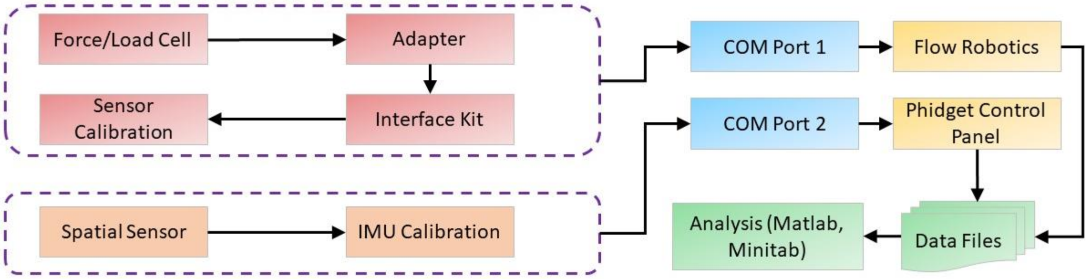

Fig. 3. Flowchart of data acquisition and processing2.3 Integrated Simulation Environment

A virtual environment was established in MATLAB to perform simulation for branch accessibility. The kinematic model of the manipulator (Kutzer, 2020) and the developed virtual tree were imported to the simulation environment. The workspace of the UR5 manipulator was calculated as shown in Figure 4(a) to estimate the working environment for simulation. The base of the manipulator was set as origin i.e. x= 0 mm, y=0 mm, and z= 0 mm. Based on the allowable workspace of the manipulator and the physical parameters of virtual tree model, the distance between the manipulator base and tree trunk was set at 400 mm (Figure 4(b)). The orientation of the virtual tree was set to make most branches accessible to the manipulator.

2.3 Field Tests

A series of field tests were conducted to address three research questions. Four different apple cultivars including Gala, Fuji, Honeycrisp, and Golden Delicious were selected for the tests. In the test one, the research question was to determine any interaction between pruning torque requirements for different cultivars. About 10 to 15 trees were selected randomly from the orchard block of each cultivar, and 105 cuts were made on branches with diameter ranges from 6 to 20 mm. The cutting angle was set as 'perpendicular to limb' orientation (straight cut) and the branch-blade contact point was set as cutter pivot. In test two (Figure 4 (a)), the research question was to determine if the torque required to cut the branches is affected by the change in cutting angle. The test was conducted only on Fuji apple trees (10 trees for about 105 cuts) and the cutting angle was set 30-degree rotation (bevel cut). The cutting torque data for straight cut was undertaken from test one dataset of Fuji trees. In test three (Figure 4 (b)), the research question was to investigate if the cutting torque changes with change in branch-blade contact point. For this test, 10 apple trees were selected from Fuji orchard block and about 105 cuts were made on different diameter branches with branch-blade contact point set as cutter center. The cutting torque data for Fuji tree branches at cutter pivot were taken from the dataset of test one.

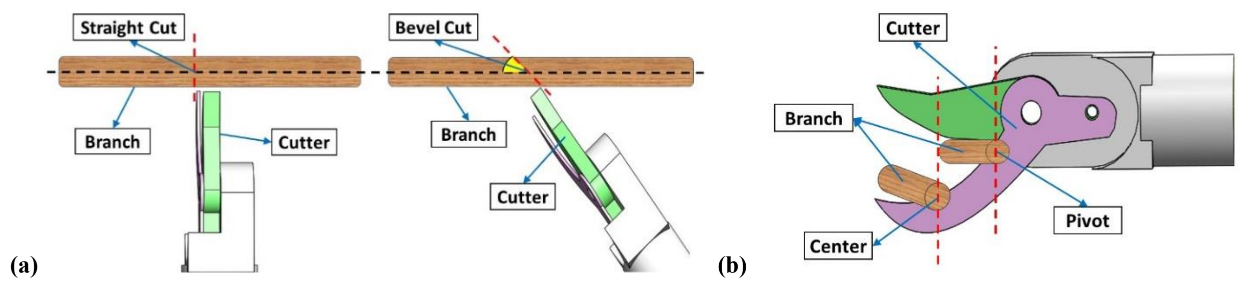

Fig. 4. (a) Illustration of different cutting angles (zero vs 30-degree angle cut); (b) Illustration of different branch-blade contact points

A series of field tests were conducted at Penn State Fruit Research and Extension Center Biglerville PA, USA (Figure 5(a-c)). In total, about 630 cuts were made for the experiment. During the tests, a vernier caliper was used to measure the diameter of the branches. The time interval between the sensor data logging was set to 0.05 s and the average sensor value was recorded to calculate the applied torque for each cut.

(a)  (b) 

(c) 

Fig. 5. (a) Field tests for branch pruning torque measurements; (b) Pruning cuts at different branch-blade contact points (cutter center vs cutter pivot); (c) Pruning cuts at different cutting angles (zero vs. 30-degree angle cut)

2.4 Statistical Analysis

All statistical analysis were performed using Minitab software. A General Linear Model (GLM) was fitted to perform Analysis of Covariance (ANCOVA) test to determine the differences in torque requirements between different cultivars at a significance level of 0.05. The cutting torque was selected as a response variable, cultivar as a categorical variable, and branch diameter as a covariate. A post-hoc Tukey test was used for paired compassion between the cultivars for cutting torque requirements. To determine the torque variations between different cutting angles (zero vs 30-degree angle) and branch blade contact points (cutter pivot vs cutter center), a separate ANCOVA test, with post-hoc Tukey test for paired comparison at a significance level of 0.05 was performed.

3. Results and Discussion

3.1 Effect of Cultivar on Pruning Torque Requirements

Table 1. present the results of the statistical analysis performed to investigate the significance in cutting torque requirements for different cultivars. The null hypotheses were that the mean torque required for cutting branches of all cultivars with any branch diameter is equal. The ANCOVA test was performed to test the hypotheses at a level of significance 0.05. The resultant F- statistic for branch diameter was estimated at 1885.77 and the F-statistic for the cultivars was 69.44. The corresponding P-value was calculated as 0.00., which was lower than the level of significance (0.05). Thus, the null hypotheses were rejected in favor of the alternate hypotheses, which suggested that amount of cutting torque varies significantly for different cultivars with changing diameter. As the GLM was fitted to check the significance, the null hypothesis for fit was that the assumed relationship in the model is reasonable, i.e., there was no lack of fit in the model. The ANCOVA test calculated the F-statistic for the Lack-of-fit as 8.65 and the corresponding P-value as 0.00. As the P-value was less than the level of significance, the null hypothesis was rejected to accept the alternate hypothesis, which suggested that there was enough evidence a lack-of-fit exist in the assumed model at 0.05 significance. The R^2 calculated from the GLM model was 84.15%.

Table 1. Analysis of Covariance (ANCOVA) for different cultivars with varying branch diameter

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Branch Diameter	1	829.25	829.246	1885.77	0.000
Cultivars	3	91.61	30.535	69.44	0.000
Error	415	182.49	0.440		

Lack-of-Fit	55	103.91	1.889	8.65	0.000
Pure Error	360	78.58	0.218		
Total	419	1151.03			

MODEL SUMMARY

S	**R-sq**	**R-sq(adj)**	**R-sq(pred)**
0.663127	84.15%	83.99%	83.74%

COMPARISONS FOR CULTIVARS
Grouping Information Using the Tukey Method and 95% Confidence

Cultivars	**N**	**Mean**	**Grouping**		
Gala	105	2.69259	A		
Golden Delicious	105	2.65862	A	B	
Fuji	105	2.44911		B	
Honeycrisp	105	1.54155			C

Means that do not share a letter are significantly different.

REGRESSION EQUATIONS

Fuji	Torque = $0.0966*Dia^2 - 0.5106*Dia + 1.1322$	R-square = 0.9763
Gala	Torque = $0.0762*Dia^2 + 0.0443*Dia - 0.9152$	R-square = 0.9919
Golden Delicious	Torque = $0.0703*Dia^2 + 0.0399*Dia - 0.65$	R-square = 0.9921
Honeycrisp	Torque = $0.0918*Dia^2 - 1.1974*Dia + 6.0801$	R-square = 0.9835

The torque applied to cut the branches of four different cultivars is shown in Figure 6. The field tests result suggested that the Gala tree branches required the highest cutting torque and the Honeycrisp tree branches cutting torque requirement was observed as lowest compared to other three cultivars. Different regression models were also tested using Matlab Curve Fitting Toolbox. As shown in the Figure 6, the pruning torque required for all four tested cultivars follows a quadratic relationship (polynomial with degree two), which is similar to torque measured for pruning Radiata Pine (Crossland et al., 1997). The quadratic equations and R^2 for individual cultivar are presented at the bottom of the table. The highest R^2 of 0.9921 was computed for Golden Delicious apple trees and the lowest R^2 of 0.9763 was for Fuji apple trees.

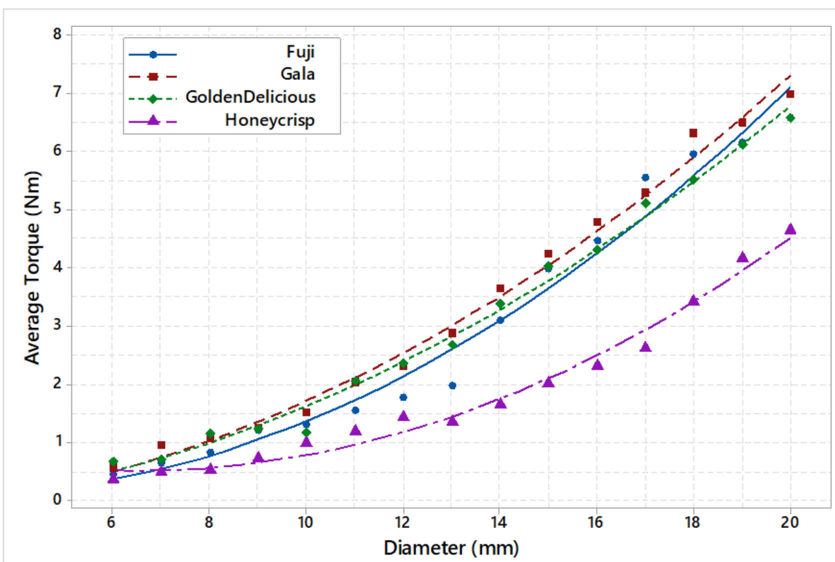

Fig. 6. Cutting torque requirements for different cultivars

The Tukey test was performed to investigate the paired comparison for significance between cultivars (Table 1). The Tukey test assigned a group letter to the cultivars (categorical variable) based on the significance. The cultivars that shared the same letter were non-significant. The Tukey's method grouping results showed that Gala and Golden Delicious shares the same group A. Golden Delicious and Fuji shares the group B, which suggested a non-significant relationship between these pairs. The Honeycrisp is assigned the group C, suggested that the torque was significantly different compared to all other cultivars. Based on the data, six paired comparison could be formed for the significance test. The results of paired comparison of Tukey 95% confidence intervals are presented in Figure. 7. The results suggested that there was a significant difference in torque for four pairs (Gala – Fuji, Honeycrisp- Fuji, Honeycrisp – Gala, and Honeycrisp – Golden Delicious) and no significance difference in torque was found for the two pairs (Golden Delicious – Fuji, and Golden Delicious - Gala).

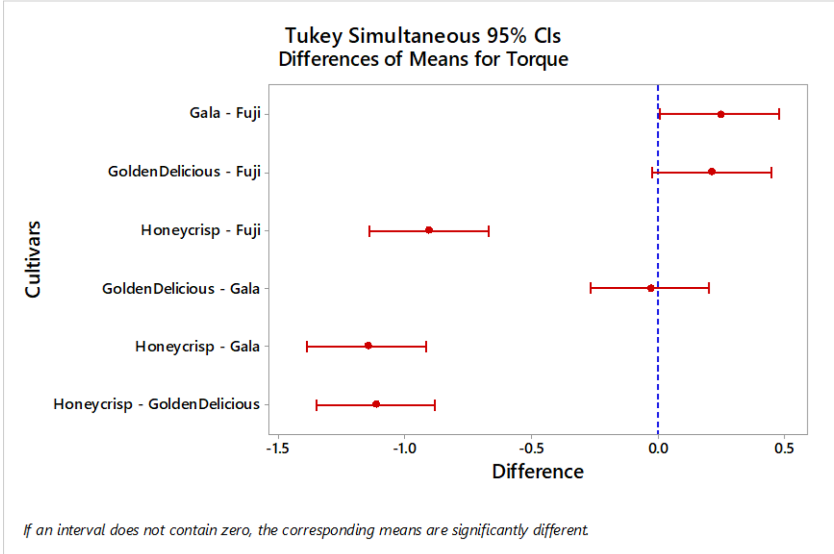

Fig. 7. Paired comparison of difference for different cultivars

3.2 Effect of Branch-Blade Contact on Pruning Torque Requirements

The statistical analysis to investigate the significance of required pruning torque for different branch-blade contact points in Fuji apple was performed (Table .2). The null hypotheses were that the required mean torque for branch cutting is equal for different branch-blade contact points and branch diameters. The ANCOVA test was performed to assess the hypotheses at a level of significance 0.05. The F- statistic for branch diameters and branch-bladed contacts were estimated at 1555.51 and 7.46 respectively, and the corresponding P-value was calculated as 0.00 and 0.007 respectively. As both P-values were less than the set significance level (0.05), there was enough evidence to reject the null hypotheses in favor of alternate hypotheses, which suggest that the means of cutting torque were significantly different. The null hypothesis for model fitting was that there was no lack-of-fit in the GLM. The F-statistic for the lack-of-fit was calculated as 11.06 with corresponding P-value of 0.00. Since, the P-value was less than 0.05 (significance level), the null hypothesis was rejected in favor of alternate hypothesis as there was enough evidence that a lack-of-fit exist in the GLM, with R^2 of 88.36%.

Table 2. ANCOVA for different branch-blade contact point on pruning torque requirements.

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Branch Diameter	1	546.396	546.396	1555.51	0.000
Contact Points	1	2.620	2.620	7.46	0.007
Error	207	72.712	0.351		
Lack-of-Fit	27	45.362	1.680	11.06	0.000
Pure Error	180	27.349	0.152		
Total	209	630.582			

MODEL SUMMARY

S	R-sq	R-sq(adj)	R-sq(pred)
2.46948	88.47%	88.36%	88.13%

COMPARISONS FOR CONTACT POINTS
Grouping Information Using the Tukey Method and 95% Confidence

Contact Points	N	Mean	Grouping	
Cutter Center	105	2.64378	A	
Cutter Pivot	105	2.41522		B

Means that do not share a letter are significantly different.

REGRESSION EQUATIONS

Cutter Center (Fuji)	$Torque = 0.0887*Dia^2 - 0.182*Dia - 0.4809$	R-square = 0.9829
Cutter Pivot (Fuji)	$Torque = 0.0966*Dia^2 - 0.5106*Dia + 1.1322$	R-square = 0.9763

Figure 8. shows the effect of branch-blade contact point on pruning torque requirements on Fuji trees. The data from the field tests suggested that a higher cutting torque is required when the branch is placed at the center of the cutter compared to the pivot of cutter. For both contact points, the cutting torque required for smaller diameter branches were not considerably different. As the diameter of the branches increases, the difference in the applied cutting torque increased between the two cutting contract points. As both datasets showed a similar rising trend, a regression model for torque requirements at cutter center was developed, which follows the similar trend of polynomial with degree two. The model for cutter-pivot cutting torque requirements in Fuji was calculated in the Section 3.1. The model equations with corresponding R^2 for both datasets

are presented in the Table 2.

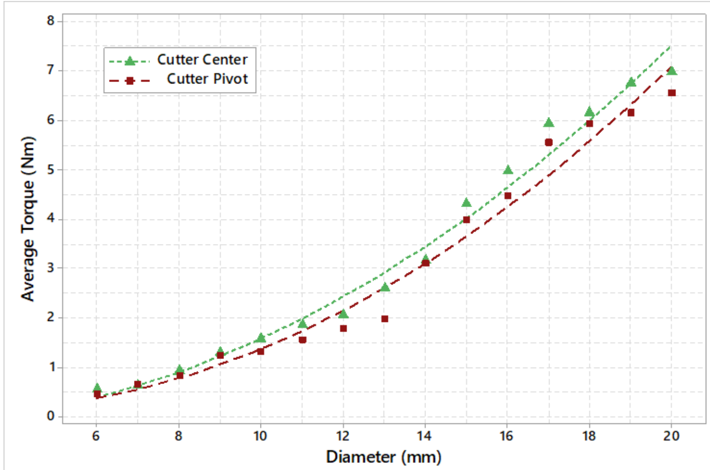

Fig. 8. Cutting torque for Fuji tree branches at different branch-blade contact points

To investigate the significance in mean differences, a Tukey test was performed for paired comparison between different branch-blade contact points. The Tukey's method grouping showed that the cutter center and cutter pivot were assigned different groups A and B respectively, which suggested that the difference was significant. Figure. 9 shows the results of paired comparison of Tukey 95% confidence intervals. The result suggested that the torque required to cut the Fuji apple trees was significantly different at different branch-blade contact points.

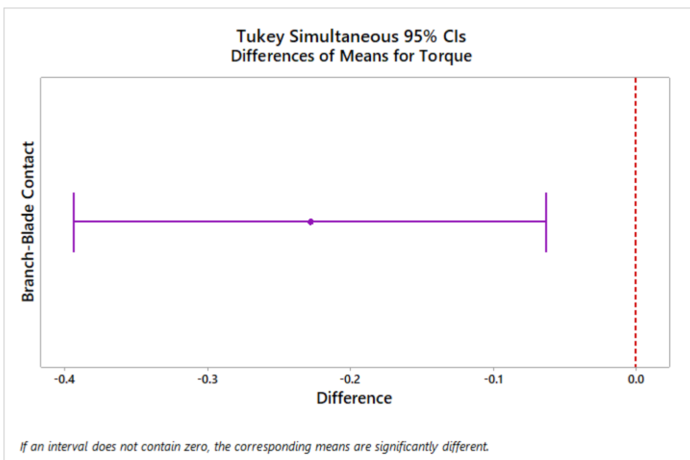

Fig. 9. Paired comparison of difference for branch-blade contacts in Fuji trees.

3.3 Effect of Cutting Angle on Pruning Torque Requirements

The effect of varying cutting angles on cutting torque requirements for Fuji trees was statistically investigated. The null hypotheses were defined as the mean cutting torque for branch cutting is equal for different cutting angles and branch diameters. Table. 2 presents the result of the ANCOVA test performed to test hypotheses at a level of significance 0.05. The F- statistic for branch diameters was calculated as 1308 and F- statistic for cutting angles was calculated as 3.58. The P-value for branch diameter and cutting angles were calculated as 0.00 and 0.060, respectively. Since, 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, which was defined as the cutting torques varies significantly with varying branch diameters. For the second hypothesis, as the P-value was higher than the set level of significance (0.05), the null hypothesis could not be rejected as there is not enough evidence to reject it. This implies that the difference in cutting torque for different cutting angles was non-significant. The null hypothesis for the GLM fitting was defined that there was no lack-of-fit in the model. The F-statistic for the lack-of-fit was calculated as 8.39 with P-value of 0.00. As the P-value was less than 0.05, the null hypothesis was rejected in favor of alternate hypothesis, which suggests that a lack of fit exist in the GLM fitting, with corresponding R^2 of 86.60%.

Table 3. ANCOVA for different cutting angle on pruning torque requirements

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Diameter	1	532.720	532.720	1308.00	0.000
Cutting Angles	1	1.458	1.458	3.58	0.060
Error	207	84.307	0.407		
Lack-of-Fit	27	46.970	1.740	8.39	0.000

Pure Error	180	37.337	0.207	
Total	209	635.312		

MODEL SUMMARY

S	R-sq	R-sq(adj)	R-sq(pred)
2.65910	86.73%	86.60%	86.33%

COMPARISONS FOR CUTTING ANGLE
Grouping Information Using the Tukey Method and 95% Confidence

Cutting Angles	N	Mean	Grouping
30 Degree	105	2.55384	A
Zero Degree	105	2.38251	A

Means that do not share a letter are significantly different.

REGRESSION EQUATIONS

30 Degree	Torque = 0.0862*Dia^2 - 0.1933* Dia - 0.1651	R-square = 0.9733
Zero Degree	Torque = 0.0966*Dia^2 - 0.5106*Dia + 1.1322	R-square = 0.9763

The effect of cutting angles on torque requirement for Fuji apple trees is shown in Figure 10. The results indicated that different cutting angles requested different cutting torques for the Fuji tree branches. The cutting torque for pruning branches at 30-degree bevel cut was considerably higher compared to zero-degree straight cut. This further explains that when the cutter is deviated 30 degrees, the effective cut size is increased, which follows the trigonometric rule (hypotenuse is larger compared to base and perpendicular of a right-angled triangle). The data also depicts that the difference in the cutting torque was less for smaller diameter branches and as the diameter increased, the difference also increased. Both datasets followed the similar trend. A polynomial with degree two regression model, with R^2 of 0.9733 was fitted for 30-degree cutting torque dataset of Fuji trees. The regression model of Fuji tree at zero-degree cutting torque was developed in Section 3.1. A Tukey test was performed for paired comparison of required torque at different cutting angles. Although, there is only one paired comparison, which was already accepted in the null hypothesis which implied that the difference was non-significant at 0.05. The Tukey's method assigned group A to both test factors the 30 degree and zero degree, which suggested that the difference was non-significant. Tukey 95% confidence intervals for paired comparison of difference in branch cutting angles is shown in Figure. 11. As the confidence interval contains zero, the difference in cutting torque required at zero and 30 degree for Fuji apple was non-significant.

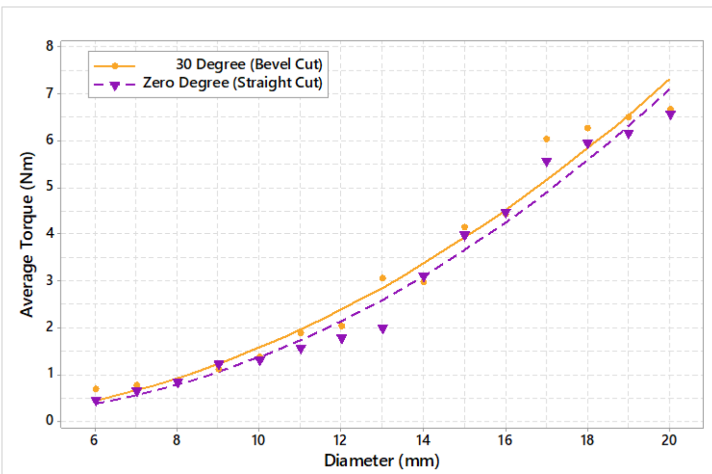

Fig. 10. Effect on torque requirements with changing cutting angle for pruning Fuji apple tree branches

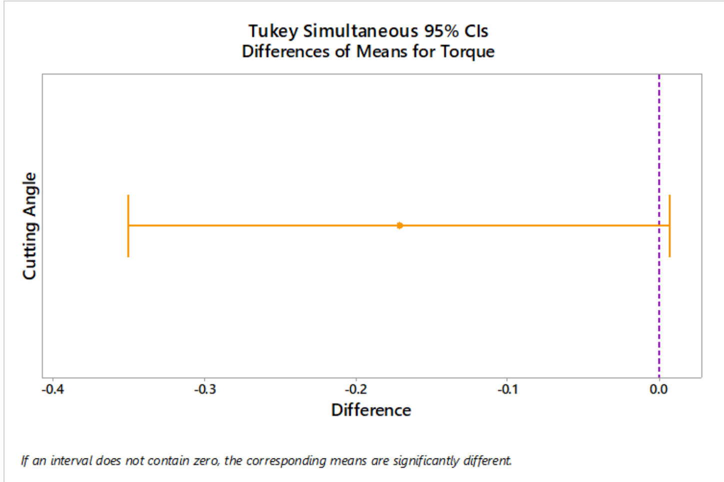

Fig. 11. Paired comparison of difference for different cutting angles in Fuji trees

Apple trees have a complex canopy architecture, with branches growing at wide orientations and narrow spaces inside the canopy, leading to the design challenges for developing robotic tree pruning system. The cutting torque required to prune branches for different apple cultivar is one of the key information required by the designers for selection of appropriate system components. The key design benchmarks include a compact pruning cutting mechanism with minimal spatial requirements that could provide sufficient cutting torque and enhanced kinematic dexterity of the pruning cutter for superior maneuverability within the canopy. Thus, the branch pruning dynamic analysis conducted in this study can provide guidance to the development of robotic apple tree pruning system. The investigation could assist the robotic system designers in the appropriate components selection to develop the cutting mechanism of the pruning end-effector. As the results indicated that Gala tree required the highest pruning torque compared to Fuji, Golden Delicious, and Honeycrisp trees, the system designers could consider the torque requirements of Gala tree as a reference for developing the pruning end-effector.

The successful robotic pruning operation also requires an effective path planning to reach the target cut point on the selected branches. For path planning, two important factors include the position of the cutter coordinate frame, and the approach poses at the target branch. The cutter coordinate frame (x, y, and z axis) defines the origin of the cutter, used by the path planning algorithm to reach, and coincide with the targeted cut point. Our results for cutting torque required for different branch-blade contact points indicated that the differences were significant, which implies that the origin of the cutter frame should be selected based on the available cutting torque of the robotic pruning system. As result suggested the cutting torque for cutter-pivot was less, the ideal case could be to define the cutter coordinate frame at the pivot of the cutter.

The cutting angle for branch pruning is critical and this become more important in case of the robotic tree pruning. The approach poses refers to the final posture of the robot at target branch, to produce the desired angle cut (bevel or straight cut). Since the cut angle does not influence the branch regrowth (Schupp et al., 2019), the cutter could reach the target point with different cutting posture to cut the branches. As the apple has complex canopy structure, the path planning scheme estimate the robot posture by automatically avoiding the obstacle branches (Zahid et al., 2020c). However, as the posture deviates from straight to bevel cut, the effective cut size (cross-sectional area) become larger, require higher cutting torque. From the results, we found that the cutting torque required for bevel cuts are larger compared to the straight cut, but the difference was non-significant for a 30-degree bevel cut in Fuji trees. However, due to complex tree canopy, the robot may have to attain a different cutting posture (higher than 30-degree cut), which may result in higher cutting torque. Thus, it is essential to estimate the torque at different cutting angles and the highest cutting torque should be selected for developing the robotic cutting mechanism, to produce a separation cut.

During the tests, it was observed that the applied cutting torque varied with the change in the position (location) of the selected branch in the tree canopy. For example, the cutting torque applied for branches in the upper side of the tree and the lower side could be different due to inconvenience of working stature for a human worker. However, the branches were selected randomly from each section (top, middle and bottom) of the tree to ensure the reliability of the samples. Alongside, the pruning cuts were applied at different locations on the selected branches including the middle, and close to the origination points on each branch. Meanwhile, it was observed that when the cut was made close to the trunk (origination point), the reachability of the cutter was reduced. This observation was documented for all postures investigated in this study including blade-branch contact point (cutter center and cutter pivot) and cutting angle (zero and 30 degree). For example, for cutting some of the branches at origination point, the cutter was not able to attain the cutting posture of straight cut as the cutter hit the trunk, and for some of the branches, the cutter failed to attain the posture for 30-degree angle (bevel cut). Similar problem was observed when the branch-blade contact point (cutter center and pivot). This reduced reachability of the cutter posture was greatly affected by the branch angle (too large/small branch angle), diameter, and blade size. Further investigations are required to develop a model for estimating the minimum distance (closet) the cutter could reach to the origin of branch with a certain angle and diameter, could be used by path planning algorithm to automatically select the final posture of the robot.

This dynamic analysis for branch pruning provides the preliminary guidelines for designing a cutting mechanism of end-effector for robotic pruning of apple trees. As the maximum component sizes are limited due to complex apple tree canopy, this analysis is particularly important to make a design assessment such as what size of motors or actuators is required, or whether a mechanical advantage will be required or not, etc., to provide the required cutting torque. The selection of larger components due to the overestimation of the cutting torque could lead to higher spatial requirements, negatively affecting the robotic pruning operation. Alongside, to estimate the maximum cutting capabilities of the pruning robot, the information of cutting torque 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 & branch age, etc., however these was not considered during the experiment. In future, more tests will be conducted to investigate the effect of these factors on cutting torque requirements for different apple cultivars. Besides, the effect of branch-blade contacts and cutting angles on torque requirements will also be studied.

4. 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 to a manual pruner, and a series of field tests were conducted. Statistical analysis was performed, and the following conclusions were drawn:

1. The cutting torque required to prune branches of different apple cultivars varies significantly because of differences in specific gravities. To develop an end-effector with sufficient cutting capabilities, the components selection for cutting mechanism should consider the cutting torque requirements of the target cultivar for efficient robotic pruning operation.
2. The branch-blade contact points significantly affected the torque required to cut the branches for the tested Fuji apple trees. This should be considered for defining the end-effector cutter frame during the automatic path planning of robot for reaching the target cut point.
3. Although bevel cut increased the cutting torque requirements for Fuji apple trees comparing to the straight cut, the effect was statistically non-significant at 30 degree cut angle. A larger angle cut could have a large difference in the torque requirements, which needs to be investigated.

The results of the experiment are vital to develop a cutting mechanism for automatic pruning of apple trees. The branch position and age are also important parameters that could influence the cutting torque. In future, tests will be performed considering the branch positioning and age to investigate the variation caused due to these factors. Alongside different cutting angles and cut points will also be investigated for different apple cultivars.

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