A Study of Chainsaw Kickback

D. Arnold
J. P. Parmigiani

Abstract

Chainsaw kickback is a serious safety concern for both experienced and novice operators. A key to developing improved kickback control systems is a better understanding of saw motion during kickback and the development of improved methods for distinguishing kickback from normal saw operation. In this study, accelerometers and gyroscopes were mounted to a battery-powered electric chainsaw and to a midsize, gasoline-powered chainsaw, and data were collected during normal cutting and kickbacks. These sensors measured accelerations along the guide bar and perpendicular to the bar as well as rotational velocities toward the operator's torso. Results from the battery-powered saw showed that accelerations during normal cutting and kickbacks had peak magnitudes of from ~2 to ~6 g and from ~6 to ~8 g, respectively, and that rotational velocities typically reached over 600°/s during a kickback. Analysis of these results showed that the gyroscope alone, using a threshold value of 300°/s, was effective in distinguishing normal cutting from kickback. Results from the gasoline-powered saw showed the same general trends as those with the battery-powered saw; however, the rotational velocities during a kickback were greater, typically exceeding 1,000°/s. Through the use of machine learning techniques, a more effective method than a simple threshold for distinguishing kickback from normal saw operation was developed. Using this method, kickback was determined very reliably and often when the deviations from the rotational velocities corresponding to normal cutting were small. Implementation of these findings could lead to improved kickback control systems on chainsaws.

Kickback is a significant safety concern for chainsaw operators. It can be defined as a rapid movement of the chainsaw toward the user during cutting, often initiated by the saw tip contacting a solid object. This movement is usually unexpected, so the likelihood for significant injury is high, particularly among novice users. Typical kickback injuries consist of the removal of a wide swath of flesh, often resulting in wounds filled with dirt, oil, and wood debris (Pratt 1979, Smith 2000, Koehler et al. 2004). The severity of these wounds makes kickback the chainsaw-related injury most likely to be life-threatening (Pratt 1979). Chainsaw operator training and protective clothing can be effective in reducing the number of kickbacks occurring and the severity of subsequent injuries (Kenyon 1989, Tsioras et al. 2014). Additionally, to address chainsaw safety, an American National Standards Institute (ANSI) standard has been developed.

ANSI Standard B175.1 ''[e]stablishes safety requirements for the manufacture and use of portable, hand-held, gasoline-powered chain saws'' (American National Standards Institute 2012). The standard includes specifications for a kickback-testing machine, the corresponding testing procedures, and a metric for quantifying the kickback tendency of a given chainsaw. The test machine consists primarily of a mounting frame that allows rotation of the saw about its center of gravity and in the plane of its bar, a slider system that moves a wooden coupon onto the tip of the bar at varying angles of incidence, and sensors and data acquisition equipment to measure response. The testing procedure consists of running the saw at typical operating speeds, orienting the bar parallel to the slider system, moving the coupon rapidly onto the bar tip to cause kickback (i.e., causing the saw to rotate rapidly about its center of gravity), and measuring the rotation angle and kinetic energy of the saw and coupon resulting from the kickback event. The testing procedure is repeated for varying coupon angles-of-incidence until a maximum saw energy is obtained. Using these test data, a metric for evaluating kickback severity, the calculated kickback angle (CKA), is determined. The CKA was originally intended to simulate an average person's reaction and predict the forces needing to be applied by operators to arrest kickback. However, simplifying assumptions made in deriving the CKA calculation algorithm and the limitations of the test machine in replicating human response have, in practice, resulted in the CKA not being predictive in this manner. Even so, the CKA is a useful parameter used by

The authors are, respectively, Graduate Student and Associate Professor, Senior Research, Oregon State Univ., Corvallis (drewdarnold@gmail.com, parmigjo@engr.orst.edu [corresponding author]). This paper was received for publication in October 2014. Article no. 14-00096.

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manufacturers to indicate the relative tendencies for a given chainsaw–and–saw-chain combination to kick back.

Roberson and Suggs (1991) attempted to more accurately replicate the human response to kickback. In their work, a human-mimetic device was designed to match the anthropomorphic properties of the average adult male's upper body. For example, ball joints were placed at the shoulder and elbow joints. Actuators were attached to each and programmed to respond as a human. Kickback was simulated by driving a flywheel, with speed and inertia typical of a small-to-medium chainsaw, into the nose of a chainsaw equipped with a bar but no chain. Output from the device was compared with data collected from human subjects equipped with sensors placed over key muscle groups. The results differed, and it was concluded that the approach had limited success.

In prior work, as described above, the focus of the approaches taken to determine the characteristics of kickback was to create laboratory devices. This approach is inherently limited by the ability of mechanical and electromechanical components to replicate the actual conditions and behavior of a human operator experiencing kickback during chainsaw operation. The work described in this article took a distinctly different approach. Here, kickback was studied by placing sensors directly on commercial chainsaws and having humans, with appropriate protection, operate the saws under both normal-cutting conditions and during kickback. This approach was used both to identify and quantify the motion of a chainsaw during kickback and to analyze this motion to distinguish normal cutting from the onset of a kickback.

The sequence of topics for the remainder of this article is as follows: First, a brief explanation of chainsaw components and operation is given, followed by a description of the chainsaws and sensors used in the experimentation. Next is a discussion of testing conducted with a battery-powered chainsaw in which basic motion characteristics of kickback are identified. This is followed by a discussion of testing conducted with a gasoline-powered chainsaw in which a method is described for distinguishing the onset of kickback from normal cutting. Lastly, conclusions are presented.

Chainsaw Components and Operation

The typical chainsaw, shown in Figure 1, consists of three primary components: the power head, the guide bar, and the saw chain. The power head contains either a gasoline engine or an electric motor, and it provides the driving force for moving the saw chain. Attached to the power head are the handles (front and rear) and the hand guard. In typical operation, the operator places one hand on each handle. Movement of the hand guard away from the front handle (i.e., toward the guide bar) activates a chain brake, causing the saw chain to come quickly to a stop. This movement can occur either by the operator's hand striking the hand guard (assuming the operator's hand is properly positioned on top of the front handle) or through inertia by rapid rotation of the power head in the plane of the guide bar. The guide bar is attached to the power head and provides mechanical support and control of the saw chain. The bar tip is the free end of the bar not connected to the power head. The saw chain contacts the work piece and performs cutting. As shown in Figure 2, the saw chain itself typically consists of three types of links: drive links, cutter links, and tie straps. Drive links engage a sprocket on the power head to propel the saw chain. Cutter links consist of a depth gauge and a chisel cutter; the depth gauge controls the size of the chip removed by the chisel cutter. Tie straps connect drive links to cutter links.

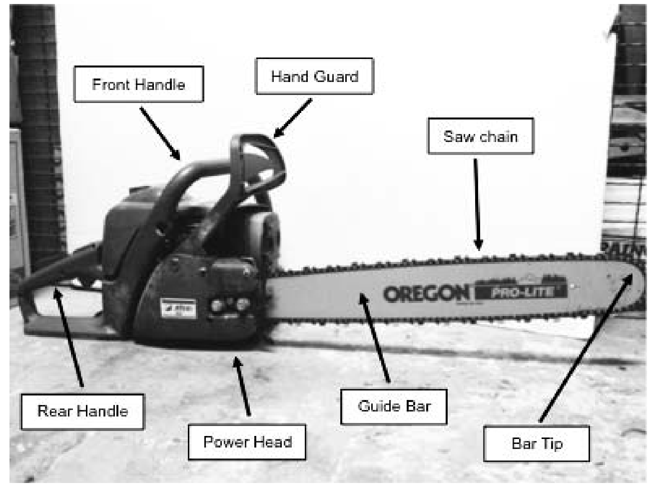

Figure 1.—A typical chainsaw with major components identified.

Normal operation of a chainsaw consists of two types of cuts: nose-clear cuts and boring cuts. Nose-clear cutting occurs when the length of the cut is less than the length of the guide bar (i.e., the bar tip extends beyond the cut). This is typically how chainsaws are used. Vertical nose-clear cutting is typically used in bucking (cutting a felled tree into shorter sections) and limbing (removing branches from a felled tree). Horizontal and bias nose-clear cutting are commonly used in felling trees and limbing. Boring, or plunge, cuts are made by pushing the tip of the guide bar into the work piece. A full-depth boring cut consists of the

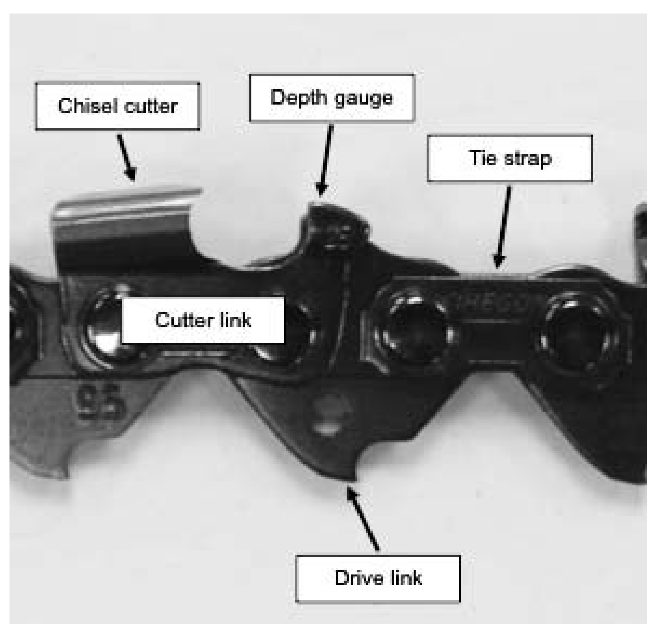

Figure 2.—Typical saw chain showing drive links that propel the saw chain, cutter links that perform the cutting with chisel cutters and limit depth-of-cut with depth gauges, and tie straps that connect these links.

guide bar being completely inserted into the work piece. Boring cuts are used in felling trees leaning unfavorably.

Kickback typically occurs when a chisel cutter, instead of cutting normally and forming a chip, cuts too deeply and becomes lodged in the work piece. This behavior is possible when the saw chain, passing over the upper corner of the bar tip, attempts to cut an overhanging object (either unintentionally in nose-clear cutting via contact with an unseen object or intentionally in boring). In this orientation, as illustrated in Figure 3, the depth gauge allows a greater-than-normal depth of cut. The lodged chisel cutter causes the energy normally used to propel the saw chain to be instead transferred to a very rapid rotation of the guide bar upward toward the user. The term *kickback* is also applied to situations in which the work piece pinches the sides of the chain as a cut is made, translating the chainsaw back toward the operator. This type of kickback is generally not as hazardous as kickback causing saw rotation and will not be discussed further in this article.

To address the danger of kickback, the US Consumer Product Safety Commission (USCPSC) requires that all chainsaws be equipped with at least two of the following three mechanisms: a low-kickback saw chain, a nose guard, and a chain brake. Low-kickback saw chains have an additional type of link, a bumper link, ahead of the cutter link that reduces the depth of cut when the saw chain passes over the bar tip. This reduces kickback tendency, but it also reduces cutting efficiency. Nose guards cover the nose of the guide bar, preventing it from contacting the work piece. This virtually eliminates the possibility of kickback but limits the functionality of the chainsaw. In practice, many users remove nose guards. A chain brake, as described previously, actuates during rapid rotation of the power head, typically as a result of kickback. However, large rotations of the saw (over 45°) are required for actuation. Most chainsaw manufacturers comply with the USCPSC requirement by using low-kickback chains and chain brakes.

Experimental Methods

Data for both normal cutting and kickback were collected using sensors located in a plexiglass box attached to the underside of the power head. Sensors consisted of MEMS accelerometers to measure linear acceleration and MEMS gyroscopes to measure rotational velocity. All sensors were calibrated by the manufacturer. Both sensor types were connected to a laptop computer for data collection via a National Instruments USB 6211 multifunction data acquisition module attached to the operator's waist. Two chainsaw-and-sensor combinations were used in testing. The first, shown in Figure 4, consisted of an Oregon PowerNow 40-V, 1.3-kW, battery-powered electric saw with a 14-inch bar instrumented with four Analog Devices one-axis sensors: an ADXL001-250 accelerometer (22 kHz, ±250 g), an AD22281 accelerometer (24 kHz, ±70 g), an ADXRS620 gyroscope (2.5 kHz, ±300°/s), and an ADXRS652 gyroscope (2.5 kHz, ±300°/s). The ADXL001-250 accelerometer was oriented to measure accelerations perpendicular to the bar and positive in an upward direction (denoted by the y axis). The AD22281 accelerometer was oriented to measure accelerations along the bar and positive away from the operator (denoted by the x axis). The gyroscopes were oriented to measure the rotational velocity of the saw in the plane of the bar, with positive rotation defined as being toward the operator's torso. The second chainsaw-and-sensor combination consisted of an Efco 152 3.4-hp (2.53-kW), gasoline-powered saw with an 18-inch bar instrumented with three sensors: an STMicroelectronics LIS331HH accelerometer (three axes, 1 kHz, ±24 g), an STMicroelectronics LY3100ALH gyroscope (one axis, 140 Hz, ±1,000°/s), and an InvenSense ISZ-500 gyroscope (one axis, 140 Hz, ±500°/s). Sensor selection was based on an anticipated greater signal magnitude than with the first chainsaw-and-bar combination and with consideration for an eventual commercial product application of this research. The LIS331HH accelerometer was oriented to measure accelerations along the length of the bar (the x axis as defined for the battery-powered saw) and perpendicular to the bar (the y axis as defined for the battery-powered saw). The gyroscopes were used as previously described for the battery-powered saw. All data were acquired at a rate of 1,000 samples per second for accelerometers and 5,000 samples per second for gyroscopes.

Experimental Results and Analysis

Battery-powered chainsaw

Data collection using the battery-powered saw consisted of 115 normal-operation cuts and 109 kickbacks. The normal-operation cuts consisted of 35 nose-clear vertical

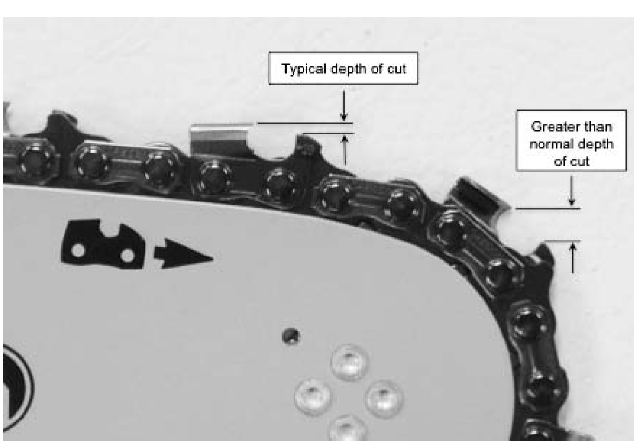

Figure 3.—Depth-gauge links allow a greater depth of cut when passing over the upper bar tip, which can cause kickback

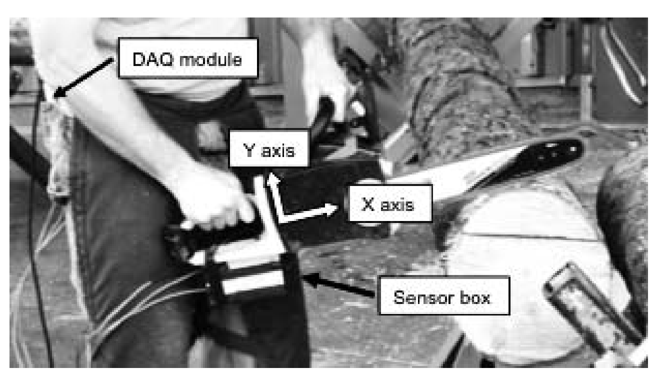

Figure 4.—Data collection using the battery-powered saw consisted of MEMS accelerometers and gyroscopes in a sensor box attached to the power head and a data acquisition module attached to the operator's waist. Positive orientations for acceleration are shown.

cuts, 16 nose-clear bias cuts, and 10 boring cuts on a horizontal 12-inch fir log (*Pseudotsuga menziesii*), 9 nose-clear horizontal cuts on a horizontal 8-inch fir post, and 45 nose-clear vertical cuts on a horizontal 2-inch ash branch (*Fraxinus latifolia*). The kickbacks were performed by attempting boring cuts on a horizontal 12-inch fir log with the upper section of the bar tip. Four different saw operators participated in the testing. Analysis of the resulting accelerometer and gyroscope data showed that differences between operators and work piece size and composition were not significant.

Analysis of data from the battery-powered saw began with an examination of the accelerometer data. During normal cutting, accelerations along the x and y axes tended to be in-phase (i.e., tended to reach extreme positive values together and extreme negative values together) and to reach peak magnitudes of between ~2 and ~6 g. In other words, during normal operation, the saw tended to have a random motion either upward and away from the operator or downward and toward the operator. A typical sample of normal-cutting data is shown in Figure 5A. During a kickback, peak accelerations along the x and y axes tended to be out of phase (i.e., one tended to reach an extreme positive value when the other tended to reach an extreme negative value, and vice versa) and to reach peak magnitudes of between ~6 and ~8 g for about 50 milliseconds. That is, during a kickback, the saw tended to first accelerate upward and toward the operator and then downward and away. This likely corresponds, respectively, to the period of time when the saw chain is in contact with the log and the period of time immediately subsequent, when contact is lost. Figure 5B shows typical data from a kickback.

Next, the gyroscope data were analyzed. During normal cutting, variations in rotational velocity were relatively small, with typical peak values usually well under 100°/s. During a kickback, however, a distinct increase in rotational velocity occurs, as shown in Figure 6. Maximum rotational velocity was typically over 600°/s. The increase in rotational velocity during a kickback showed significant variation in maximum rotational velocity, number and size of minor peaks, and overall duration; however, a rotational velocity of 300°/s or greater was found to correspond consistently to a kickback. That is, if the magnitude of rotational velocity exceeded a threshold value of 300°/s, it could be concluded that a kickback was occurring. The driving force causing saw rotation during a kickback begins when a chisel cutter becomes lodged in the work piece. As energy previously used to drive the saw chain is transferred to the saw and bar, the rotational velocity increases. This increase continues, with peaks and valleys, as long as the saw chain is in contact with the work piece. The maximum rotational velocity occurs just as the saw chain is losing contact with the work piece. After contact is lost, rotational velocity decreases and, as the operator regains control, returns to normal.

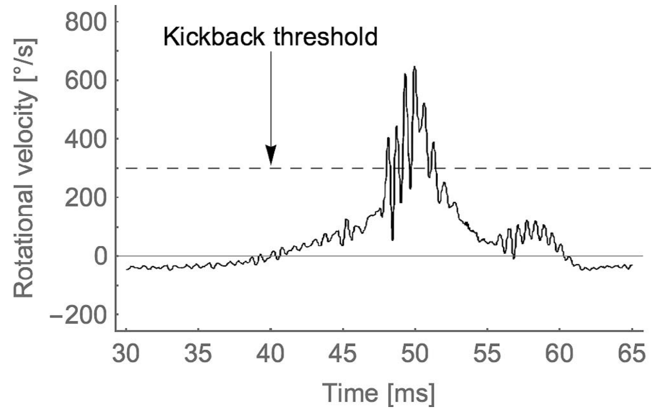

Figure 6.—Typical gyroscope output from the battery-powered saw during a kickback. Rotational velocities over 300°/s consistently indicated that a kickback was occurring.

Given these acceleration and velocity motion characteristics, analysis was conducted to determine which could better be used to distinguish normal cutting from the onset of a kickback. To do so, an objective function, φ, is defined as follows:

$$\varphi = \alpha a_y - \beta a_x + \gamma \omega_z \tag{1}$$

where a_y is the y-axis acceleration, a_x is the x-direction acceleration, ω_z is the rotational velocity, and α, β, and γ are weighting factors to be defined. Values of this function are calculated using acceleration and velocity data that

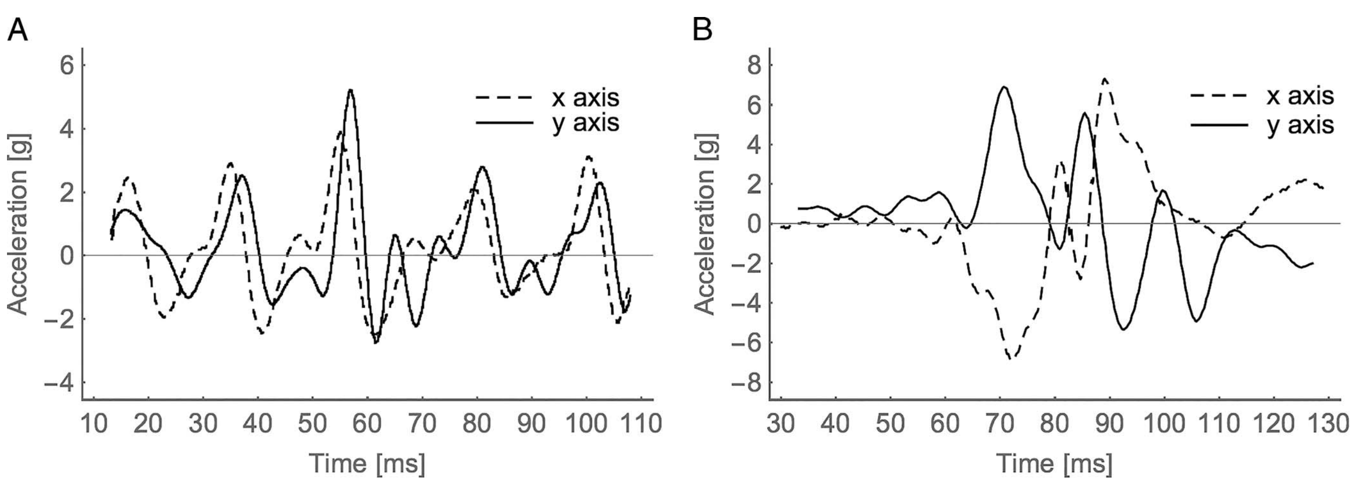

Figure 5.—(A) A typical stream of accelerometer data when using the battery-powered saw to perform normal cutting showing in-phase behavior of x- *and* y-*axes accelerations. (B) A typical stream of accelerometer data when kickback is occurring with the battery-powered saw showing out-of-phase behavior of* x- *and* y-*axes accelerations.*

correspond to normal cutting and to kickbacks and are denoted by φ_{NC} and φ_{KB}, respectively. The magnitude of the difference between values of φ_{NC} and φ_{KB} are quantified by the parameter Δ_φ as follows:

$$\Delta_\varphi = \frac{\varphi_{KB} - \varphi_{NC}}{\varphi_{NC}} \quad (2)$$

Thus, large values of Δ_φ correspond to large differences in saw motion during normal cutting and saw motion during a kickback, and small values correspond to small differences. Maximum values of Δ_φ indicate the most effective means of distinguishing normal cutting from the onset of a kickback. Maximum values of Δ_φ were calculated by varying the values of the weighting factors systematically. Details of this procedure and can be found in Arnold and Parmigiani (2011). Results indicated that for typical saw use, a gyroscope alone was sufficient and that combining a gyroscope with accelerometers did not significantly improve the ability to distinguish normal cutting from the onset of a kickback

Gasoline-powered chainsaw

Data collection using the gasoline-powered saw consisted of 114 normal-operation cuts and 141 kickbacks. The normal-operation cuts consisted of 56 nose-clear vertical cuts and 58 nose-clear bias cuts all on a horizontal 12-inch fir log. The kickbacks were performed by attempting boring cuts on a horizontal 12-inch fir log with the upper section of the bar tip, as was done with the battery-powered saw. All normal-operation cuts and kickbacks were performed by the same operator.

In general, the data collected with the gasoline-powered saw showed similar trends as the data collected using the battery-powered saw. The accelerometers displayed the same in-phase and out-of-phase behavior. However, as with the battery-powered saw, the gyroscope provided the most useful data. As with the battery-powered saw, significant variation was found in maximum rotational velocity, number and size of minor peaks, and overall duration of a kickback. In general, however, the maximum rotational velocity was greater for the gasoline-powered saw, typically exceeding 1,000°/s during a kickback. Testing with the battery-powered saw showed that exceeding the threshold value of 300°/s of rotation indicated a kickback was occurring. This was also found to be true for the gasoline-powered saw. However, observation of the data suggested that a method other than a simple threshold might be more effective in distinguishing between normal cutting and kickbacks. To explore this, machine learning techniques were used.

The term *machine learning* describes a variety of mathematical techniques in which rules for classifying data (i.e., mapping inputs to outputs) are determined from an analysis of the data itself and not from predefined criteria. A familiar example is commercial Web sites that recommend items for purchase to frequent buyers. Such recommendations are made from analysis of prior purchases and not from previously known characteristics of the buyer. In this example, the classification that occurs is the mapping of the all of the products for sale on the Web site (the inputs) to those products that a given customer may wish to purchase (the outputs). Other examples for the application of machine learning methods are image recognition (e.g., from many images of a traffic intersection, determine which contain a pedestrian) and spam filtering (i.e., from many e-mails, identify those that are not of interest). In each example, the computer ''learns'' from the accumulated data how to make accurate classifications or predictions.

Support vector machines (SVMs) are a type of machine learning. The SVM method used in this study is from the work of Cortes and Vapnik (1995). When using SVM, the data are separated into two sets. The first is a training set containing input data and the corresponding classification for each input. The second is a test set containing only input data. The SVM method creates models, called classifiers, that classify the data contained in the test set based only on an analysis of the training set. SVM classifiers are defined to make the distinction between classifications as large as possible. While all of the data in the training set are analyzed, only the data in the training set resulting in the largest distinction between classifications are selected to define the classification criteria. The selected data are referred to as the support vectors.

In using SVM to distinguish normal cutting from kickback, there were two primary goals. The first was to accurately classify a given set of gyroscope readings as either corresponding to normal cutting or corresponding to kickback and, in doing so, generate neither false positives nor false negatives. The second was to perform the classification of a kickback as early in the event as possible (i.e., determine that a kickback is occurring when the deviation from rotational velocities corresponding to normal cutting is as small as possible). Physically, early kickback classification corresponds to classification well before the saw chain loses contact with the work piece. Accomplishing both of these goals can be challenging in that they are, to a large extent, contradictory. High accuracy will tend to correspond to the relatively large rotational velocities that occur well into a kickback. Early classification will occur when rotational velocities are relatively small and confusion with normal cutting likely to occur. The resolution of this problem was achieved through the simultaneous use of a series of multiple SVM classifiers. Some were specifically designed for early classification, some for high accuracy, and some for spanning the region in between. This provided the opportunity for both early correct classification and the certainty of eventual correct classification.

This approach was applied to the gyroscope data obtained from the gasoline-powered saw. The commercial SVM package LIBSVM was used for all SVM calculations. Ten classifiers were created spanning the region from normal cutting to what will be referred to as the kickback identification (ID) point. Based on data collected from the battery- and gasoline-powered saws, the kickback ID point was defined as the first peak in gyroscope readings at or above 300°/s. Using this point, instead of simply using the first gyroscope reading above 300°/s, was found to give improved classification. The classifier series and kickback ID point are illustrated in Figure 7. Based on typical gyroscope readings during a kickback, the 10 classifiers spanned a total of 28 milliseconds, with each classifier spanning 10 milliseconds and overlapping with the subsequent classifier by 8 milliseconds, as shown in Table 1. Ten training sets were used to create the 10 classifiers. The training set data were a combination of normal cutting and kickbacks. Preliminary studies using SVM were conducted to select the 200 most effective 28-millisecond

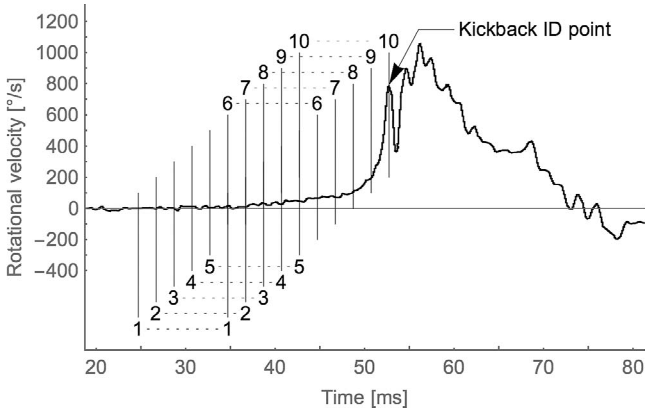

Figure 7.—Typical gyroscope output from the gasoline-powered saw during a kickback showing the time periods corresponding to each of the 10 over-lapping SVM classifiers and the reference point (i.e., the kickback identification point) used to locate the 10th classifier

time periods of normal-cutting data from the approximately 1 hour of total normal-cutting data gathered. Kickback data were obtained from randomly selecting 86 kickbacks from the 141 kickbacks measured. In each case, data were selected according to the period of time before the kickback ID point corresponding to the associated classifier.

The resulting stack of 10 classifiers was then applied to a test set of all the remaining data, which consisted of 55 kickbacks and nearly an hour of normal cutting. The test set data were analyzed in 10-millisecond intervals. Each interval was evaluated by each of the 10 classifiers. If any of the 10 classifiers indicated that a kickback was occurring, then the data were classified as being part of a kickback. If kickback classification did not occur, the 10-millisecond interval was moved 2 milliseconds forward in time (i.e., 2 milliseconds of new data were added, 2 milliseconds of old data were dropped, and the resulting shifted interval was tested). This procedure was followed for all the data in the test set. This proved to be both very accurate, with each of the 55 kickbacks being correctly classified with no false positives, and very effective, in that classification tended to occur early, with the earliest detection 29.4 milliseconds before, the latest 0.6 milliseconds before, and the average 11.7 milliseconds before the kickback ID point.

Conclusions

The goals of this study were to characterize the motion of a chainsaw during a kickback and to distinguish between normal cutting and the beginning of a kickback. In achieving these goals, data were collected from both a battery-powered electric saw and a midsize, gasoline-powered saw. For both saws, MEMS accelerometers were used to measure linear acceleration of the power head, and MEMS gyroscopes were used to measure rotational velocity of the power head. Results from both saws indicated that random vibration of the saw during normal cutting corresponded to accelerations only slightly less than those of a kickback. However, the normal-cutting accelerations tended to be in phase, and the kickback accelerations tended to be out of phase. Accounting for this difference resulted in a greater difference between normal-cutting and kickback accelerations. For both saws, however, gyroscopes provided the most useful data. A threshold value of 300°/s was found

Table 1.—Ten support vector machine classifiers were used, each corresponding to 10 milliseconds of saw operation and overlapping the subsequent classifier by 8 milliseconds

Classifier no.	Time before kickback ID point (ms)
1	28–18
2	26–16
3	24–14
4	22–12
5	20–10
6	18–8
7	16–6
8	14–4
9	12–2
10	10–0

to consistently correspond to a kickback. The gasoline-powered saw tended to produce kickbacks having greater peak rotational velocities than those of the battery-powered saw. This is likely due to the dominance of the first of two competing effects: the greater power of the gasoline-powered saw and the greater rotational inertia of the longer bar of the gasoline-powered saw. Increased power will tend to increase rotational velocity during kickback, and increased rotational inertia will tend to decrease it. Through the use of machine learning techniques and data from the gasoline saw, kickback was very accurately detected and distinguished from normal cutting an average of 11.7 milliseconds before the first peak in rotational velocity above 300°/s.

These results are significant in that they provide information on the motion corresponding to a chainsaw kickback from data collected from actual production chainsaws used by experienced operators conducting typical cutting operations. They demonstrate that kickback can be distinguished from normal cutting consistently and early in the kickback event. Implementing these results could lead to a better means of kickback control. Combined with the work of others in, for example, alternative lubricants (Skoupy et al. 2010) and vibration exposure (Hartsough et al. 1987, Rottensteiner and Stampfer 2013), this could lead to significantly safer and more environmentally friendly chainsaws.

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