The Influence of Knife Dullness on Poultry Processing Operator Exertions and the Effectiveness of Periodic Knife Steeling

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A novel procedure is described to establish knife steeling schedules for poultry and meat-processing operations based on increased force due to knife dullness from repetitive use to minimize operator exertions and physical stress associated with work-related musculoskeletal disorders. Knife dullness was quantified using a novel apparatus described in this article that measures the area cut by a knife into a carrageenan gel target for a controlled dynamic load at the knife handle. Two meat-cleaning jobs in a poultry-processing plant were studied. One job required significantly more force and a greater number of cuts than the other. Eight experienced operators participated in the study. Four freshly ground and honed knives were randomly used by each operator for 4, 45, 75, or 125 cutting cycles, measured for dullness and reconditioned by the operator using a steel sharpening rod. An empirical model for knife dulling and reconditioning was developed, and the corresponding increase in force was predicted for various cutting and reconditioning frequencies. The model showed that it took 57 and 125 cutting cycles for the high- and low-force jobs, respectively, to achieve a similar reduction in target surface area of 30%. This reduction in target surface area corresponded to a similar percentage increase in force needed for the same cut in carrageenan gel as compared to a freshly honed knife as measured using strain gages. This method may be used in meat processing plants for determining effective reconditioning schedules that reduce operator exertions with minimum effect on quality and productivity.

Keywords: ergonomics, hand tools, musculoskeletal disorders, poultry processing

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The poultry processing industry is continuously making improvements in areas such as mechanization, automation, and ergonomics to process poultry more productively. In this evolution of poultry manufacturing, many things have changed over the years except for the use of a basic tool, the knife. One reason for this is simply that the knife is an extremely versatile tool that cannot be rivaled by mechanization or automation without sacrificing a significant amount of precision and dexterity. Consequently, skilled human labor in the use of a knife is critical for tasks such as meat cleaning, in which fat is removed from a number of distinct parts of poultry and no two pieces of poultry are alike. The knife has thus received considerable attention in the area of ergonomic research.

A number of studies have been performed analyzing characteristics of the knife and its use that do not directly deal with the topic of operator exertion. Examples of such studies include evaluation of knife handle guarding,(1) investigation of the effect of cutting table height and angle on workload demands,(2) analysis of workplace factors that contribute to musculoskeletal disorders of meat process workers,(3,4) and studies of knife design.(5–7)

This study focuses on knife dulling and operator exertions, an area where extensive research has not been done.(8) A number of other knife characteristics and their associations with forceful exertions have been investigated to optimize specific features of the knife. The relationships between force of exertion and handle shape and size have been examined at length.[9–14] Maximum forces in simulated cutting tasks have also been examined for subjects using different hand–handle orientations.[15,16] The influence of blade angle and handle diameter on grasping force and forearm flexor muscle EMG signals has been investigated as part of an ergonomic evaluation of knives used in poultry processing operations.[17] The influence of gloves on the force/torque exertion capability of workers has also been considered.[18,19]

One characteristic of the knife dealing with operator exertion that has received considerably less attention and that potentially has great impact on operator effort is blade dulling. The role of knife condition in the slitting of plastic films has been investigated,[20] showing that cutting force varies linearly with blade-edge radius. It is widely recognized that knife blade condition not only contributes to the pace and precision of manual cutting tasks, and therefore directly affects productivity and product quality, but also that it affects the amount of force required to perform cutting tasks. Considering that the frequency of cuts for a deboning operation at a typical poultry processing plant was estimated to be more than 15,000 per operator per shift,[21] one should be concerned with any nonessential force required to perform cutting tasks. The additional force needed to overcome a dull blade is consequently an important factor in the prevention of musculoskeletal disorders of the upper limb.

Knife use has been associated with increased risk of musculoskeletal injuries in food preparation occupations.[22,23] The high prevalence of carpal tunnel syndrome[24] in the meat industry and tenosynovitis or peritendinitis[25] among meat and poultry handlers has been widely reported. Armstrong et al. found that poultry processing jobs that had especially high incidence rates of work-related musculoskeletal disorders of the upper limb were for jobs that require frequent hand exertions.[21] The thigh-skinning department had the greatest incidence rates of musculoskeletal complaints in the poultry processing plant investigated, with 129.6 cases per 200,000 hours worked.

The current study was performed in a turkey processing plant located in the midwestern United States. Knife condition was quantified using a novel knife dullness tester that measures the area cut by a knife into a carrageenan gel target for a controlled load at the handle. These data were shown to be directly proportional to force as the knife blade is dulled, utilizing the inherent Newtonian properties of the tester. Eight poultry plant operators used professionally ground and honed knives for four different cutting periods over two jobs. The knives were then reconditioned by the operators on the plant floor by steeling, and tested to analyze the extent of reconditioning on the overall sharpness of the blade after specific amounts of initial dulling.

METHODS

Subjects

Six female and two male operators volunteered for the study. All participants except one described themselves as right-handed. Their ages ranged from 24 to 44 years with a mean of 30.9 years and a standard deviation of 6.6 years. Experience in meat cutting ranged from 11 to 109 months, with a mean of 48.4 months and a standard deviation of 42.1 months.

Task

The two jobs selected for study were in the white meat cleaning department: the side gristle/top fat job, and the skin removal job. Both jobs were on the same cleaning table and had identical production rates. The mean elapsed cycle time based on video analysis for each jobs was 6.1 sec per piece, with a standard deviation of 0.57 sec. A nominal production rate for these jobs was 10 pieces per minute.

The side gristle/top fat job consisted of removing gristle and fat from whole turkey breasts by cutting the tissue behind it. This job was selected because it involved the most intensive and forceful cutting of the six white meat cleaning jobs. Three cuts were made per piece. The skin removal job consisted of removing skin from whole turkey breasts. This job was selected because it involved small force exertions. One cut was made per piece.

Every participant used four similar ground and honed knives for 4, 45, 75, or 125 cutting cycles in a random order. Each knife was then tested for dullness using the test apparatus described in this article. The four knives were then returned to each subject for manual reconditioning with a smooth steel rod. Subjects were instructed to recondition each of their own knives using eight swipes, four up and four down. All knives were then retested for dullness using the test apparatus. The basis for the number of cutting cycles at which to test the knives for dullness and the number of steeling swipes to be used by the subjects is explained in the Discussion section.

Materials and Experimental Apparatus

All knives used were Forschner Victorinox (Wimberley, Texas) 40513 stainless steel 6-inch straight blade knives. This knife is commonly used in poultry processing. The knives were sharpened and honed daily by knife room personnel on a Cozzini Honer-Edger (Chicago) model HE7–2000, using a single step sharpening process. This is a V grind, and it is performed once per day (employees, however, use two knives daily).

The knife test apparatus, shown in Figure 1, contained a pendulum with an adjustable weight on one end and a jig to hold the knife on the opposite end. A swab of food coloring stain was applied to the knife blade after mounting the knife in the test fixture. When the pendulum was released, the knife fell against a carrageenan gel target and produced cuts of different cross-sectional areas, depending on the sharpness of the knife. The cut target surface area was made visible by the food coloring.

A Casio (Dover, N.J.) QV-100 digital camera captured an image of the knife imbedded in the target surface along with a calibration scale. The camera had a charge couple device with 360,000 pixels. The lens had a fixed focus of F2.8/f = 4.2mm. The AutoCAD (Autodesk Inc., San Rafel, Calif.) program was used to trace the digitized image and calculate the area cut by the knife blade in millimeters squared. The reported area therefore corresponds to the area of the knife that penetrated the target.

The carrageenan powder used to make the target was a gel agent and is used in a variety of food applications.[26] The targets were prepared by mixing 23.03 grams of Satiagel® RPI 9/230 carrageenan powder and 1 L of boiling water. Targets were poured into Styrofoam™ cups, covered with aluminum foil, and left to cool overnight in a refrigerator. The gel was then removed from the cups and cut into 3-cm cubes.

Two control knives were tested for sharpness but not used for cutting at the beginning and end of the high-force job experiment, to determine if there were any changes in the carrageenan gel during the course of the experiment, which lasted more than 3 days. The mean change from start to end was only 0.53 (SD=7.46) mm^2, which was considered to be insignificant.

The knife was slowly dropped against the carrageenan target

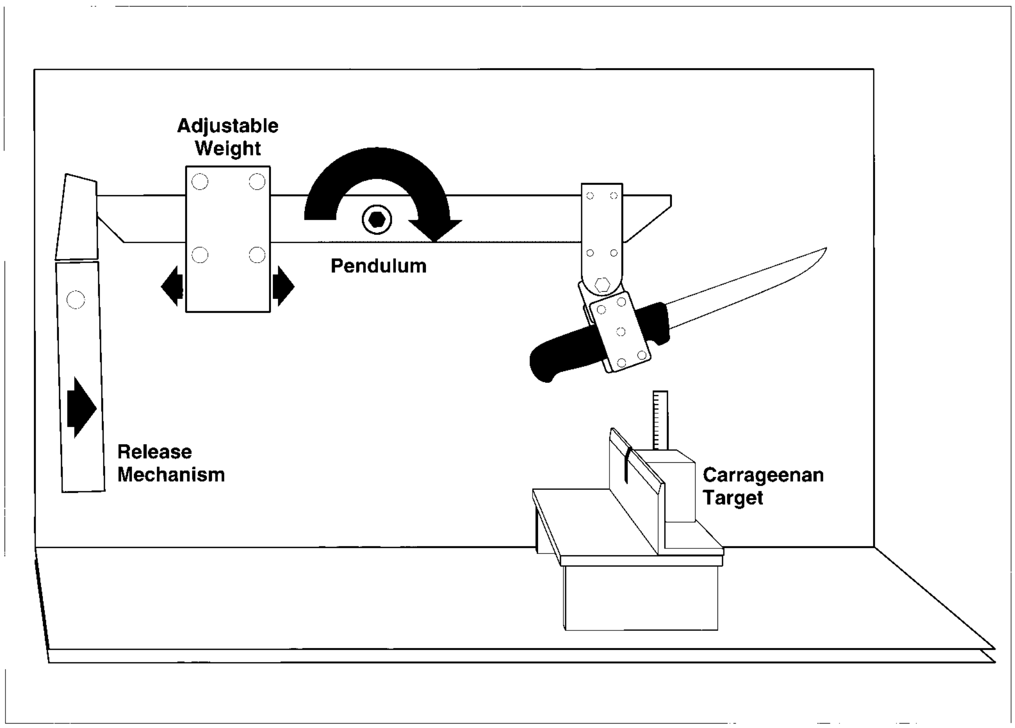

FIGURE 1. Knife test apparatus

with a force that was controlled by a simple pendulum. The knife test apparatus operates on the principle that the target area cut by the knife is proportional to the pressure opposing the knife by the carrageenan gel target, and consequently, sharpness is inversely proportional to the dulling knife blade cutting edge, a measure of knife blade condition. This provides a means from which to predict an increase in force exertion via the area cut in the target because the pressure exerted by the knife against the carrageenan target is the ratio of the blade force to the blade surface area.

$$P_{knife\ on\ target} = F_{blade}/A_{blade}$$

where P_{knife} is the pressure exerted by the knife against the carrageenan target, F_{blade} is the force exerted by the knife blade against the carrageenan target, and A_{blade} is the knife blade cutting edge surface area.

Because there is a controlled load at the handle for each test trial, the pressure from the knife against the target is greater when the knife blade is sharp and has the smallest cutting edge. The pressure is proportionally reduced as the knife dulls. This relationship was tested experimentally using a knife similar to the one used in the study, with strain gauges affixed to both sides of the blade. Strain gauges were mounted in a pocket milled from the knife blade near the handle to measure shear strain at the center of the knife blade. This measure corresponds with the force applied against the knife blade and is insensitive to the point of force contact along the length of the blade.[27] The strain gauge output was calibrated for force exerted against the knife handle. The calibration was done by pressing the knife against a wood block coupled to a strain gauge load cell. The segment of the knife blade that contacted the wood block was the same segment that contacted the carrageenan targets during sharpness tests. The calibration was modeled as a linear function and resulted in the equation:

$$F = 117.08(V) + 0.6308$$

with a coefficient of determination $R^2=0.996$, where F is the force exerted against the knife handle and V is the voltage strain gauge output ($F[1,598]=156,345$, $p<.01$).

This strain gauge modified knife was placed into the knife sharpness tester for given levels of dullness and dropped into a carrageenan target. The relationship between surface area cut and force measured from the strain gauge modified knife is shown in Figure 2.

The figure shows that when the force exerted by the knife against the target was small, the knife blade was sharp and had the smallest cutting edge. The force linearly increased as the blade

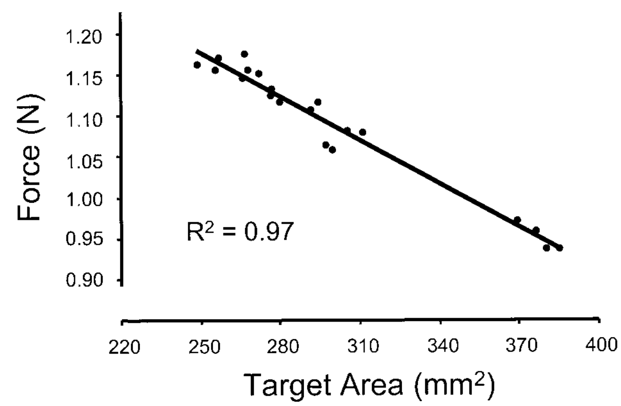

FIGURE 2. Relationship between knife blade force and target area in carrageenan gel

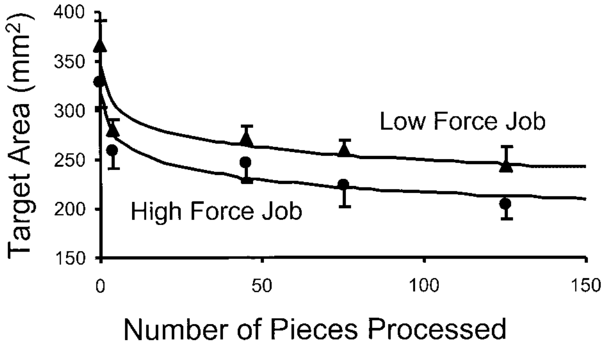

FIGURE 3. Relationship between knife dulling (measured by the carrageenan target area cut) and the number of cuts for the low- and high-force jobs. Average for all employees and plus or minus one standard deviation is indicated. Plots of regression equations in Table I also are included.

dulled and cutting edge surface increased. This linear relationship with a coefficient of determination $R^2=0.968$ provides direct support to the principle that target surface area is proportional to the pressure opposing the knife by the carrageenan gel target and consequently inversely proportional to the sharpened knife blade cutting edge surface, a measure of sharpness, and blade force ($F[1,18]=542.2$, $p<.01$).

RESULTS

The mean target surface area cut for both the high- and low-force jobs is plotted against the number of cutting cycles or poultry pieces processed by the eight subjects in Figure 3. This reduction in surface area for both jobs as the number of cutting cycles increased represents a proportional increase in force as the knife becomes dull after repetitive use without reconditioning.

Knife dulling was empirically modeled for each job as an exponential function using linear regression and is plotted in Figure 3. These functions resulted in the equations shown in Table I, where A is the target surface area cut and N is the number of poultry pieces processed. The model showed that it took 57 and 125 cutting cycles for the high and low jobs, respectively, to achieve a reduction in target surface area of 30%, corresponding to a similar increase in force needed for the same cut.

Changes in surface area cut by knives on the test apparatus after reconditioning with a steel rod following 4, 25, 75, and 125 cycles of cutting is shown in Table II. Analysis of variance indicates no significant differences in the increased knife sharpness when reconditioning the knives after different initial levels of dullness ($F[3,34]=1.33$, $p<.29$). Reconditioning a knife blade subjected to any level of dulling within the experimental parameters was found to increase the surface area cut by that knife blade by 54.84 (SD=31.81) mm², which corresponds to a 17.4 and 16.2% decrease in force for the high- and low-force jobs, respectively. Therefore, a constant term for reconditioning with a steel rod is included in the model.

TABLE II. Manual Reconditioning with a Steel Rod

Number of Pieces Processed Before Reconditioning	Number of Knives Tested	Change in Surface Area Cut After Reconditioning (mm²) Mean	Standard Deviation
4	10	46.628	33.453
45	10	50.315	35.964
75	8	49.693	34.536
125	10	71.707	19.552
Average		54.843	31.810

The knife dulling model illustrated in Table I and the reconditioning data were used in predicting the maximum level of knife dullness, as measured by surface area cut, given different frequencies of reconditioning for both the high- and low-force jobs. After a number of dulling and reconditioning cycles the surface area cut by the knife according to the knife dulling model decreased and became constant. That constant value is used as the maximum level of dullness given a specific frequency of knife steeling. These regression models may be combined to predict the resulting level of knife dullness for a given number of cutting cycles and frequency of knife steeling. The resulting predictions for the high-force job are shown in Figure 4.

The percentage increase in force given different reconditioning schedules for both the high- and low-force jobs is plotted in Figure 5. This percentage increase in force is a measure of the decrease in target area cut from its initial value when the knife was ground and honed. Both the high- and low-force jobs experienced a sudden increase in force between a frequency of reconditioning of approximately 1 and 20 pieces and then encountered a leveling off of increase in force.

DISCUSSION

Due to the recognized importance of knife sharpness, poultry processing facilities have invested significant amounts of time and money in programs that help maintain the condition of their knives. Too frequent knife steeling is costly because the operation does not add direct value to the product. Alternatively, too little reconditioning has the undesirable consequence of increasing forceful exertions and effort needed to accomplish the manual cutting task. This increase in forceful exertions can increase the risk for musculoskeletal disorders of the upper limb and adversely affect productivity and product quality.

Interviews conducted in the plant with employees and line supervisors showed that employees in these jobs were instructed to recondition their knives after every three to five pieces processed. This recommendation came from feedback by employees when asked how many cuts they felt they made before their knives began to require reconditioning.

TABLE I. Knife Dulling Regression Models

Job	Target Area in Dulling[A]	R^2	Significance
Low force	$A = 345.772(N + 1)^{-0.071}$	0.863	$F(1,3) = 18.9$, $p < .03$
High force	$A = 317.168(N + 1)^{-0.083}$	0.907	$F(1,3) = 29.2$, $p < .02$

Note: n = 5 subjects low force, 6 subjects high force.
[A]A = target area (mm²); N = number of cuts.

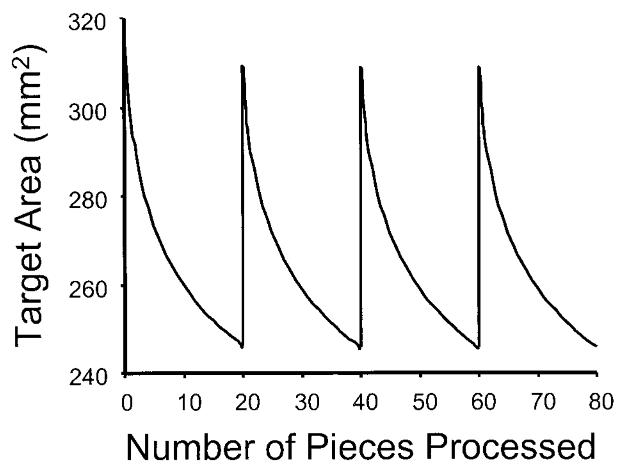

FIGURE 4. Example of sharpening/reconditioning model predications for steeling after 20 cycles

The cross section of a freshly ground and honed knife blade[28] shows that the honed area of the blade has a larger included angle than the edge area directly above it, thus making it sharper than the edge area. It is this honed area that employees describe as the most significant factor in providing the knife's sharpness. It was discussed with more than a few employees how a knife that is not honed feels significantly duller than one that has been. The honed area is only 0.006 inches deep, which might explain why knives tend to dull after only three to five cycles. After this many cycles the honed area tends to roll over and the employee begins to cut with the edged area, which is not as sharp. Steeling is a process of lining up tiny microscopic teeth on the blade and straightening a wire edge. Knives were thus tested for dullness after four pieces processed to investigate this loss in sharpness, and the data shows this loss clearly.

Rather than every three to five cycles, video analysis revealed that employees tended to recondition their knives by steeling every 4.5 min, or after 45 pieces processed, which was included in this study. Factors other than dullness apparently influenced reconditioning frequency. Employees and supervisors were asked further what was the absolute maximum time that they would use their knives between reconditionings. Their responses varied, with answers of between 7 and 15 min, which corresponds to about 75 and 125 cutting cycles, also included in this investigation.

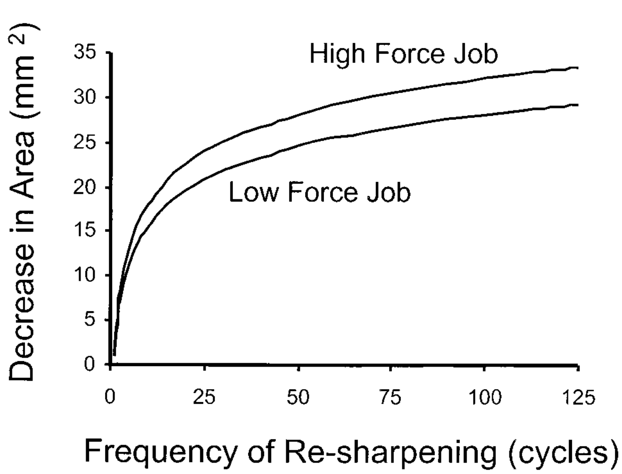

FIGURE 5. Resulting increase in force plotted against frequency of reconditioning

Video analysis showed that employees averaged 7.9 swipes per reconditioning with a standard deviation of 4.31. Because of this, the subjects in this study were asked to steel knives using 8 swipes so that the influence of reconditioning on regaining knife sharpness could be investigated.

This study found that when reconditioning took place after every 6 cutting cycles for the high-force job and 9 cutting cycles for the low-force job, knife dulling increased cutting force by 15% for the same cut in carrageenan gel as compared with a fresh knife. After 13 and 21 cycles for the high- and low-force jobs, respectively, cutting force increased by 30%. Consequently, significant force increases may be anticipated for too infrequent reconditioning, as is illustrated in Figure 4. Increased cutting force may increase fatigue onset and the risk of work-related musculoskeletal disorders.

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