CUTTING MOMENTS AND GRIP FORCES IN MEAT CUTTING OPERATIONS AND THE EFFECT OF KNIFE SHARPNESS

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ABSTRACT

The force exposure associated with meat cutting operations and the effect of knife sharpness on performance and productivity have not been well documented. Specialized hardware was used to measure grip force and reactive moments with 15 professional meat cutters performing lamb shoulder boning, beef rib trimming and beef loin trim operations in a field study conducted in two meat packing plants. A system for measuring relative blade sharpness was developed for this study. Mean and peak cutting moments observed for the meat cutting operations, averaged across subjects were 4.7 and 17.2 Nm for the shoulder boning, 3.5 and 12.9 Nm for the rib trim, and 2.3 and 10.6 Nm for the loin trim, respectively. Expressed as percent of MVC, mean grip forces of 28.3% and peak grip forces of 72.6% were observed overall. Blade sharpness was found to affect grip forces, cutting moments and cutting time, with sharper blades required statistically significant lower peak and mean cutting moments, and grip forces than dull knives. Efforts aimed at providing and maintaining sharp blades could have a significant impact on force exposure.

INTRODUCTION

High forceful exertions, high repetition rate, and awkward postures are risk factors for musculoskeletal disease of the upper extremities (MSDUEs) (Bernard,1997). Silverstein et al. (1986) observed a significant increase in MSDUEs among workers at jobs where frequency and force were both categorized as high. Hand tool use was involved in 9% of compensable work-related injuries in 1984 (USA), of which the upper extremities were the body part injured in greater than half the cases (Mital, 1991). In industries such as meat packing and automobile upholstering, where hand tools are used extensively, the incidence of MSDUEs can be much greater than the average (US Department of Labor, 1996). Though a dose response relationship in MSDUEs has not been demonstrated definitively, an intervention based on reducing exposure to known risk factors seems a reasonable ergonomic approach. A comprehensive ergonomic evaluation should include measurements of the force requirements and the repetitiveness of the task being analyzed (Silverstein et al., 1986).

In the meat packing industry, knowledge of the applied forces (moments) and grip forces associated with knife use is important for the study of the relationship between force exposure and injury, identification of high-risk techniques, and validation of task redesign. Task frequency can be measured by observational methods, and upper extremity posture can be estimated by observational methods or measured directly by goniometric methods, but little quantitative information is available regarding force exposure during meat cutting tasks.

A review of the literature yielded two reports of direct measure of either the cutting moments during meat packing operations (Stoy and Aspen (1999) and McGorry et al., (2000)). These studies used instrumented knife handles to measure applied forces and moments. A laboratory analysis of the surface electromyographic (EMG) activity of upper extremity muscles during simulated meat cutting tasks has also been performed (Grant & Habes, 1997).

In addition to the lack of quantification of forces associated with meat cutting, other factors fundamental to knife use in meat packing operations have not been subjected to extensive scientific scrutiny. It has long been accepted in the meat packing industry that " a sharp knife is a safe knife". At least two assumptions underlay this axiom. It assumes that a sharp knife requires less exertion by the operator and thus could minimize exposure. The second assumption is that a more predictable and precise cut produced by a sharp knife poses less risk of laceration or stabbing injuries. A sharper knife is also assumed to improve productivity and product quality.

Related to, or perhaps a reason for the lack of data about the role of blade sharpness is the lack of sharpness measurement systems. One approach to non-destructive testing of knife blades was reported by Szabo and Radwin, (1998). In laboratory testing using a gel cutting target, a linear relationship was reported to exist between force applied by the blade and the surface area of the cutting edge, a measure of blade sharpness. Bishu et. al. (1996) performed a laboratory study of forces used in cutting a bologna with a sharp and dull knife.

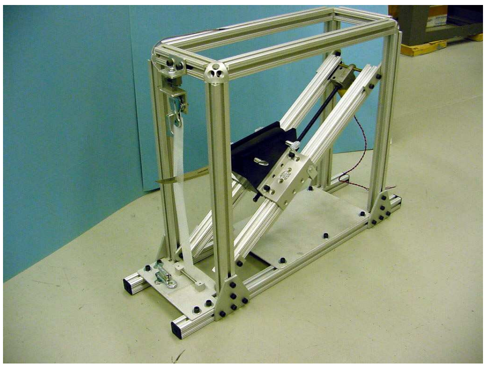
The purpose of the present field study is twofold. The first goal is to quantify the cutting moments and grip forces in several meat cutting operations performed by professionals in meatpacking plants. The second goal of the study was to provide insight into the affect that blade sharpness has on the grip forces and cutting moments.

METHODOLOGY

Subjects
Fifteen meat cutters (14 male and one female) working on the production line at lamb and beef processing plants in New Zealand were recruited for participation in the field study. The experimental protocol was explained to the workers, and each gave written informed consent for their participation. Anthropometric data and demographic information were collected.

Grip force and cutting moment measurement
An instrumented knife was fabricated duplicating the handle and blade configurations of the boning knives most typically used in the two plants. The instrumented knife has strain gauges mounted on the handle core, which allow resolution of the grip force vector and blade reactive moments. The 10 blades from each of the knives were cut, and welded to a fitting allowing for attachment to the handle core. Replicas of the handles were cast in polyurethane, cut and mounted to the handle core. Photographs of the original Victorinox knife and the instrumented version are presented in Figure 1. Further description of the instrumentation and the fabrication process are presented elsewhere (McGorry, 2001). The signals from the strain gauges in the knife handle were amplified and sampled at 100 Hz by an A/D converter and stored in the memory of a laptop computer.

Blade sharpness measurement
Since no commercially available devices were available for quantitative non-destructive testing of the blade sharpness, a device for the purpose was designed and fabricated by one of the authors (P. Dowd). See Figure 2. The underlying principle of the measure is that a sharp blade produces a smaller reactive force than does a dull blade. A linear actuator to was used to drive a knife blade downward at approximately a 45° angle through a plastic mesh at an approximately 40 mm/sec rate. This allowed measurement of reactive forces along the entire blade



edge, in a dynamic yet controlled and repeatable manner with a reasonable approximation of a cutting motion. A mesh material was selected for the cutting media because the process of cutting through a series of independent avoided problems associated with propagation of a tear following an initial cut, which could be an issue with a solid homogeneous material. The mesh strip was clamped in a vertical orientation, with the upper end of the mesh fixed by a clamp attached to a load cell. As the blade cut the mesh from the tip to the hilt of the blade the reactive force was measured by the load cell, and the amplified output sampled at 500 Hz by an A/D converter and stored in the memory of a laptop computer.

Experimental Protocol

Following collection of the interview data, each subject was instructed in the procedure for producing a maximum voluntary contraction (MVC) for power grip and for the cutting motion (ulnar deviation). The experimental knife handle was used to measure the cutting and grip MVCs consistent with the Caldwell protocol (Caldwell et al, 1974).

Knife blades were sharpened manually by the most experienced knife sharpener on the shift. Some blades were dulled by rubbing a 400 grit polishing cloth along the entire length of blade with consistent force and were assigned to the medium and dull groups. Blades that received no additional treatment were assigned to the sharp group. Each blade was then placed in the sharpness tester, and the reactive cutting force on the mesh was recorded along the entire length of the blade.

A blade from one of the three sharpness groups was randomly assigned for testing, and was mounted on the instrumented knife handle. The subject returned to the processing line and was instructed to perform the meat cutting operation in as natural pace and technique as possible. The grip forces and reactive moments on the blade were recorded for three operations with the test blade. Following the three trials subjects were asked to rate the sharpness of the test blade using the 0 to 10 scale described above. This procedure was repeated for the remaining two blade sharpness conditions. After completing the three trial conditions, the subjects were permitted to change scores if necessary so as to rank the three blades in relative order of sharpness. Following the data collection session for each subject, the sharpness of each blade used was again measured with the sharpness tester.

In one plant six subjects completed the protocol while performing a lamb shoulder boning operation. This involved making an “oyster cut”, and removing each shoulder from the ribcage. The shoulders were then trimmed of excess fat and tissue. At a second plant five subjects performed a beef intercostal trim, or “rib trimming” operation. The purpose of this operation was to remove as much muscle as possible from between the ribs by cutting down one side of the intercostal muscle and up the other to remove the meat from the adjacent ribs. A third operation, a loin trim was performed by four subjects. This involved removing the fatty covering of the loin, removing any fat seems or excess fat and tissue from the loin so that it meets market specifications. These three operations were selected for evaluation because they represented a diversity of technique and perceived difficulty. The shoulder boning and rib trimming operation were selected because they were felt to be among the more physically demanding operations on the respective lines, yet involved differences in technique. The loin trim provided a good contrast, being considered to be less strenuous but requiring skillful cuts to produce a high quality, high value product.

To assure the ability to generalize the study findings it was important to verify that the experimental knives were of a sharpness level consistent with those typically used by meat cutters in the plants. To achieve this a random sample of “working” knives was taken. Ten knives belonging to meat cutters working on the shift were randomly sampled and tested using the sharpness testing procedure.

Data Analysis

Ninety data files were processed (15 subjects x 3 sharpness conditions x 2 replications). The second and third replications of each condition were used for the analysis, so as to minimize potential variation due to learning or accommodation occurring during the initial replication. Calibration constants were applied to the data from the eight strain gauges. Next the data was smoothed using a 50 msec centered average smoothing window. The data from the six gauges in the handle were averaged to produce a single mean grip force value for each data sample. A vector summation of the cutting and lateral blade reactive moments was performed resulting in a single resultant cutting moment for each data sample.

The data was visually examined, and the beginning and end of the cutting operation were marked. The time period between these two points was referred to as Total time. A 0.5 Nm resultant moment on the blade was found to be satisfactory as a threshold for cutting activity. Each data point was evaluated, and if the cutting moment exceeded the 0.5 Nm threshold that grip force and cutting moment data point was classified as a cut. The summation of the time when the threshold was exceeded was referred to as Cutting time. The peak and mean values of both the cutting moment and the grip force during Cutting time were determined for each replication. A numerical integration of both the cutting moment and the grip force during the Cutting time was also performed. The average of the mean and peak values for the two replications was calculated for each variable for each of the three conditions.

Blade sharpness was determined by calculating the average of the downward component of the cutting force over the entire test period. The mean force (kg) was used to represent the overall sharpness of the entire blade surface. The sharpness measurements taken before and after each trial was averaged to give a mean sharpness value for that trial. The blade sharpness from the 10 "working" knives randomly sampled from the meat cutters was calculated in similar fashion.

RESULTS

Comparison of the three cutting operations

Of the three tasks evaluated, the lamb shoulder operation had the highest peak grip forces, and peak and mean cutting moments. The results are presented in Table 1.

Table 1: Grip forces, cutting moments, time and performance measures for the three cycles of cutting tasks

Operation	**Lamb shoulder mean (s.d.)**	**Beef rib mean (s.d.)**	**Beef loin mean (s.d.)**
Total time (s)	53.6 (13.2)	77.9 (20.8)	43.4 (7.8)
Cutting time (s)	20.7 (6.0)	46.5 (10.3)	13.0 (4.0)
Peak cutting moment (Nm)	17.2 (3.4)	12.9 (2.2)	10.6 (2.6)
Mean cutting moment (Nm)	4.7 (1.1)	3.5 (1.0)	2.3 (.4)
Integrated cutting moment (Nms)	102 (47.9)	161 (48.5)	31.9 (15)
Peak grip force (N)	135.9 (40.6)	97.9 (19.4)	75.1 (21.5)
Mean grip force (N)	41.6 (10.8)	46.2 (13.0)	31.2 (3.9)
Integrated grip force (Ns)	885 (405)	2,074 (469)	409 (136)
Cuts per operation	31.8 (2.4)	31.0 (10.7)	28.1 (6.5)
Operations per hour	50	40	40
Cuts per day	12,733	9,200	9,000
Cutting moment exposure / shift (Nms)	40,800	51,520	10,208
Grip force exposure / shift (Ns)	354,000	663,680	130,880

Lamb shoulder boning (n=6), beef rib trim (n=5), beef loin trim (n=4).

Cutting moment exposure / shift = integrated cutting moment x operations / h x 8 h/shift. Grip force exposure / shift = integrated grip force x operations / h x 8 h/shift.

The beef rib trim produced the highest mean grip force. The rib trim also produced the highest value for the integration of both grip force and cutting moments. The number of cuts performed per section was similar for the lamb shoulder (31.8) and beef rib (31.0) operations, but the Total time (cycle time) was shorter, and the number of sections processed per hour was greater for the shoulder operation section. The beef loin trim, had the lowest values for all the measured variables.

The effect of blade sharpness
Blade sharpness as determined by the sharpness testing device was compared to the order of rankings made the meat cutters. The rankings were in agreement in nearly 87% of the cases, and cases of disagreement were typically between the medium and dull conditions. For the cases in disagreement, the difference in sharpness between conditions was 0.1 kg as compared to 0.44 kg for the cases in agreement. This disparity in the differences suggests that in the cases of disagreement, the small differences in sharpness may have been difficult to perceive by the meat cutters. Based on these findings, the blade sharpness measurements were used to group the conditions for comparison. Overall and group blade sharpness measurements for both the experimental and "working" knives are presented in Table 2.

Table 2: Blade sharpness measurements

	Working knives		**Experimental knives**	
	Mean (s.d)	**Range**	**Mean (s.d.)**	**Range**
Overall	24.3 (7.8)	15.1 – 34.8	18.1 (3.6)	13.0 – 26.0
By group				
Sharp	15.4 (0.2)		14.7 (1.7)	
Medium	22.3 (0.9)		18.2 (2.2)	
Dull	32.6 (2.7)		21.5 (3.0)	

Randomly sampled working and experimental knives, overall and by assignment to groups (sharp, medium, dull), units = N.

Differences in cutting time, and the peak, mean, and integration of cutting moment and grip force between the medium and sharp trials, and between the dull and sharp trials were calculated for each subject. A paired t test for means was performed to test differences in the dependent variables. The significance level was set at $p<0.05$. The differences in the variables between both the medium and sharp groups, and the dull and sharp groups were significant for all variables except for the peak grip forces. A regression analysis comparing the difference in blade sharpness and the difference in mean cutting moment between the dull and sharp conditions for all subjects produced a $r2 = 0.49$ with $F = 0.004$. The same analysis between medium and sharp conditions produced an $r2 = 0.44$ with $F = 0.007$. Figure 3 provides a graphical representation of these results.

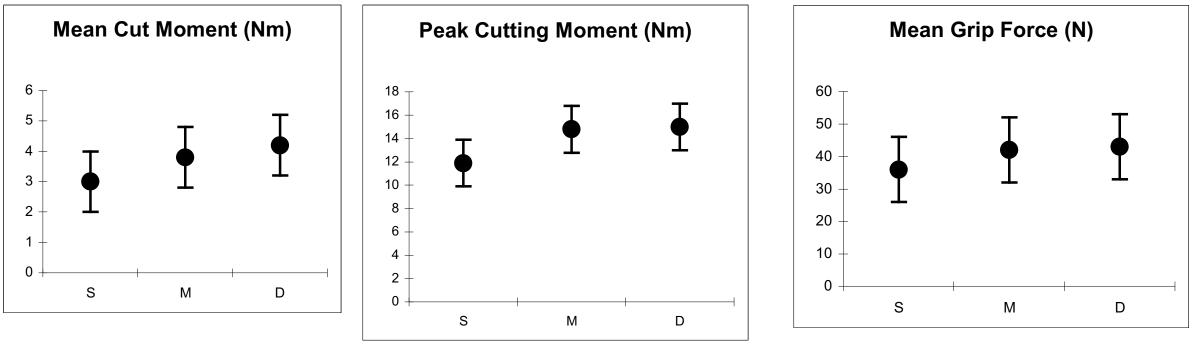


Figure 3: Peak and mean cutting moments, and mean grip force, presented with 95% confidence interval bars, under sharp (S), medium (M) and dull (D) blade conditions.

The MVC for power grip were calculated for all 15 subjects and the group mean was 152.9 N (s.d.= 39.8 N). The MVCs for cutting (ulnar deviation) were calculated for only 13 of the 15 subjects, as results for two subjects had to be rejected because of procedural errors in the tests. The group mean for the cutting MVC was 12.1 Nm (s.d.=3.0 Nm). The relationship of each subject's peak and mean grip force to their grip MVC was calculated and expressed as a percentage, for the 15 subjects. The same calculation was made for the relationship of cutting moment to ulnar deviation MVC for the 13 subjects. The results from this analysis are presented graphically in Figure 4.

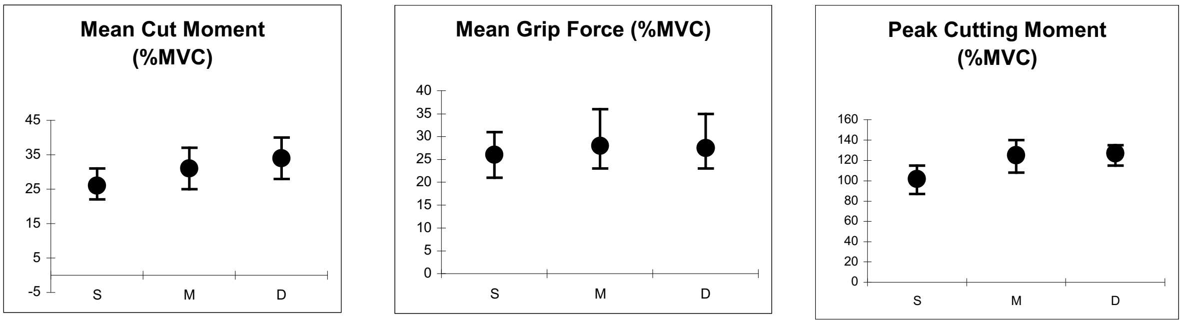


Figure 4: Peak and mean cutting moments, and mean grip force, with confidence intervals, expressed as a percentage of subject's maximum voluntary contractions, under sharp (S), medium (M) and dull (D) blade conditions.

DISCUSSION

The goal of quantifying the magnitude of the grip forces and cutting moments produced in several red meat packing operations was achieved in this field investigation. Based on the results it is clear that all three operations are highly repetitive tasks that require significant exertion. Lamb shoulder boning required higher peak grip forces and cutting moments. Though this measure does provide some insight into the nature of the tasks, it is also important to consider that the cutting operations examined in this study were all fairly complex requiring multiple cuts of varying length and intensity. The mean cutting moment and grip force are the mean of the forces above the threshold, and as such may be more representative of the sustained effort required of the task. These measure were much higher for the shoulder boning and rib trimming than for the loin trim operation. Cutting. Rib trimming which required nearly 45% more Total time per section than the shoulder boning operation, also required nearly 125% more Cutting time. As a result the integration of both the grip force and cutting moment, a reflection that the force demands of the task are much higher for the rib trimming operation. The loin trim operation had the lowest values for all the measured variables. Though less physically demanding, this operation may represent a trade off of strength for precision, as skilled trimming yields a higher quality and quantity of this more expensive cut.

The contention that these are physically demanding jobs is further supported when the grip forces and cutting moments exerted are expressed as a proportion of the subject's MVC. As a group, the meat cutters were found to be working a sustained (mean) level in excess of 28% and 32% of their maximum grip force and cutting moment, respectively. Peak exertions were found to exceed MVCs by approximately 18% overall. The fact that peak values can exceed MVC may seem counterintuitive at first glance. It is believed to be related to the fact that the peak cutting forces observed in this study tend to be impulse-like. That is, they are forceful exertions of very brief duration. The MVC protocol on the other hand is based on an isometric contraction sustained for several seconds. A potential weakness of the experimental protocol was that by necessity, MVCs for each subject were taken near in time to the their experimental trial. For most subjects this was several hours into their workday, thus their MVCs might be effected by fatigue to some degree. On could argue however, that an MVC taken near in time to the data acquisition might more closely reflect the actual capacity at that instant in time. In any case, based on the data presented in Figure 4, the required force as a proportion of MVC decreased with the used of a sharper blade.

A blade sharpness tester, designed for this study, was used to measure blade sharpness. There was good agreement between the sharpness measure produced by the test device, and the ordered rankings of sharpness given by the professional meat cutters with an average of 9.8 years of experience. Based on the random sampling of the sharpness of "working" boning, the sharpness range of the experimental knives was probably conservative. See Table 2. The random sample produced three clusters of sharpness level. The sharpest working knives were very close to the sharp experimental group, and the medium working knives were close to dull experimental group. But the working knives had a cluster of sharpness scores approximately 50% duller than the dullest knives of the experimental knives. The sample of working knives was small, and as such one should be cautious in drawing conclusions. It seems clear, however, that the experimental range of sharpness is well within the working range. A weakness of this field study was the inability to strictly control blade sharpness. Sharpening and dulling blades to precise tolerances was not practical in this field investigation. Even with this shortcoming, a regression analysis demonstrated that in within-subject comparisons between the sharp and dull blades (r2 = 0.49), and sharp and medium blades (r2 = 0.44), a large proportion of the variance by could be explained by the condition of the blade. A well controlled laboratory study could further investigate a dose response blade sharpness on grip force and cutting moments.

The within-subject analysis of the effect of blade sharpness yielded some interesting results. The results suggest improvements on the order of 20 % to 30% in cutting time, grip force and cutting moment with a sharp knife as compared to a medium or dull knife. These differences were found to be significant for mean grip force, mean cutting moment, and cutting time. These findings strongly suggest that keeping a knife sharp may decrease force exposure, as well as improving efficiency (cutting time). Such efficiency could allow for the incorporation of longer or more frequent "microbreaks", which might offer some benefits. The decreases in the peak grip force and peak cutting moments associated with the differences in sharpness between the medium and sharp, and the dull and sharp groups was not statistically significant (p= 0.116 and p=0.06) respectively. The very large variation between subjects, reflected in the large standard deviations for the test variables, a coupled with the sample size may have contributed to the lack of statistical significance. Also, the three operations were composed of multiple cutting motions, and the peak represents only the single greatest exertion of the operation. Development of a more sophisticated waveform analysis may have yielded a significant finding but seems unwarranted in light of the strength of the other findings.

CONCLUSION

In conclusion, the meat cutting operations evaluated in this study were found to be high force, high repetition tasks requiring subjects to perform at a high proportion of their physical for grip force and cutting capacity. Blade sharpness clearly had a major impact on the grip forces and cutting moments produced by the meat cutters in performance of their jobs. Efforts aimed at providing and maintaining sharp blades to workers in meat packing operations could have a significant impact on the force exposure to the upper limbs. The range of sharpness of the experimental blades was well within the range of randomly sampled knifes from workers on the shift. In fact, the experimental sharpness levels were conservative, suggesting that some workers could be expected to have exposure to even greater force levels. These results certainly suggest that development of practices aimed at improving the sharpness of blades used in meat cutting operations should have a significant impact on exposure to a known risk factor for MSDUEs.

The instrumentation developed and used in this investigation, the grip force and reactive torque sensor, and the blade sharpness testing apparatus should have utility in future investigations of meat packing operations. Quantification of additional operations would contribute to the knowledge base of the exertions involved in this industry. These measures should also prove useful in the evaluation of changes in work practices such as training programs, workstation design, job rotation and sharpening protocols in reducing exposure.

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