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Measurement of Handle Forces for Crimping Connectors and Cutting Cable in The Electric Power Industry

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Abstract

Overhead and underground line work in the electric power industry is physically very strenuous and can expose workers to musculoskeletal disorders (MSDs), particularly in the upper extremity. Crimping compression connectors—such as sleeve connectors and lugs—and cutting cables are two of the most frequent tasks that line workers perform. Line workers at many utilities in the US crimp connectors and cut cable with long-handled manual tools. However, the actual magnitude of the forces applied to the handles of these tools is not known.

The objectives of this laboratory study were to measure the forces applied to the handles of a manual press and a manual cutter in order to connect typical wire gauges and cut common cables, respectively. The handles of the manual press and cutter were attached to the drive cylinder and load cell of an Instrom Material Testing System, and peak forces exerted against the handles were measured. Results showed that the outer die of the manual press required about 50% more handle force than crimping connectors with the inner die location. The peak handle forces required to cut aluminum conductor cable as large as 2 cm diameter exceeded 500 N and were about 200 N greater than the peak forces to compress connectors manually. When the peak force data were compared to strength capabilities reported in the literature, less than 1% of the general population was found to have the maximum strength to manually make one crimp on a common overhead connector. Less than 1% and approximately 50% of the female and male general population, respectively, were found to have the maximum strength to manually cut a cable with a 2 cm diameter conductor. Handle force data from this study provide a biomechanical framework for explaining how the job demands of overhead and underground line workers could possibly cause MSDs.

Relevance to industry

Electric power utilities can review their work practices and tools in order to determine whether they can reduce the exposure of their workers to risk factors of MSDs, as well as reduce their cost of health care. Manufacturers of crimping and cutting tools can use the experimental approach in this study to measure the external forces required for their respective tools and then set quantitative force benchmarks to improve the design of their tools.

Keywords

Crimping, Cutting, Handle force(s), Pulling force(s), Line worker(s), Utility(s)

1. Introduction

This project focused on overhead and underground distribution line workers, who construct, maintain, and restore electrical power on utility poles and in manholes and vaults in a utility's distribution system. The distribution system is the flow of electricity from the substations to users (residences and businesses) and does not include transmission of electricity from the power plant to the substations. Within the distribution system, overhead line workers perform their work from either a bucket on a boom or from a climbing position on a pole, and underground line workers stand, crouch, or kneel in manholes and vaults that have ceilings as low as 6ft high. Except otherwise noted, all references to 'line workers' or 'line work' in this manuscript pertain to both overhead and underground workers.

Line work is physically strenuous and can expose workers to risk factors associated with musculoskeletal disorders (MSDs), such as tendinitis affecting the rotator cuff muscles, lateral epicondylitis (tennis elbow), and carpal tunnel syndrome. In a study of cost and nature of injury from nine electric utilities in the US from 1995 to 2001 (EPRI, December 2002), line workers had the greatest percentage of medical claim cost among all occupations (17.7%). Among all occupations, male line workers had the third highest injury rate per 200,000 h of exposure (5.51), and female line workers had the second highest injury rate per 200,000 h (17.97). The ratio of injury rates between female and male line workers was the second largest among all occupations (2.25 controlled for age). Across all occupations in the nine utilities, physical injuries of a cumulative nature (sprains and strains) comprised 36.8% of the total number of injuries and 41.6% of the total cost of injuries. In addition, sprains and strains accounted for over 40% of the injuries to the wrist for all occupations. Thus, one can conclude that a substantial portion of the injuries suffered by line workers were musculoskeletal, were

cumulative in nature, and affected the upper extremity. The report concludes that ergonomic interventions could help reduce the risk of MSDs to line workers.

Crimping compression connectors and cutting cables are two of the most frequent tasks that line workers perform. As shown in Fig. 1, compression connectors either join two cables together to conduct the flow of electricity or join a cable to a lug that plugs into equipment. Compression connectors are so reliable that some compression connectors have been in use for over 50 years. Although there are alternative tools (such as battery-operated presses) making inroads among US utilities, the most common method for crimping compression connectors is with a manual press. As illustrated in Fig. 2, a common manual press is a Burndy (FCI, Manchester, NH, USA) model ♯MD6, which has a compound mechanism, weighs 3 kg, and has two 64 cm length handles. Fig. 3, Fig. 4 illustrate typical postures of overhead line workers crimping compression connectors with an MD6 from a bucket and pole, respectively. A single compression connector requires at least three crimps for overhead applications and sometimes six or more for underground purposes. It is not unusual for overhead line workers to make 50 or more crimps on compression connectors in 1 day. Typical sizes of wire pairs that overhead line workers connect with compression connectors range from ♯6 to ♯2 AWG (conductor diameters of 0.47 and 0.74 cm, respectively) to 1/0–4/0 AWG (conductor diameters of 0.94 and 1.33 cm, respectively) (Kurtz et al., 1998).

Fig. 1. An aluminum compression connector joining two cables. This photo shows the jaws of a Burndy MD6 enclosing the connector before the connector is pressed over the cables. When the connector is pressed, the aluminum deforms around the cables and makes an extremely tight connection.
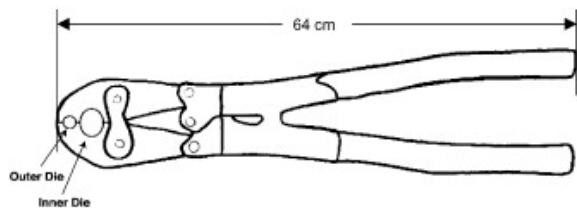

Fig. 2. The Burndy MD6 manual compression press. The connector is placed in either the outer or inner die and squeezing the handles deforms the connector over the pair of wires, thereby making a solid connection between two wires. Courtesy of EPRI (December 2001).

Fig. 3. An overhead line worker crimping a compression connector with a manual compression press from a bucket. Courtesy of EPRI (December 2001).
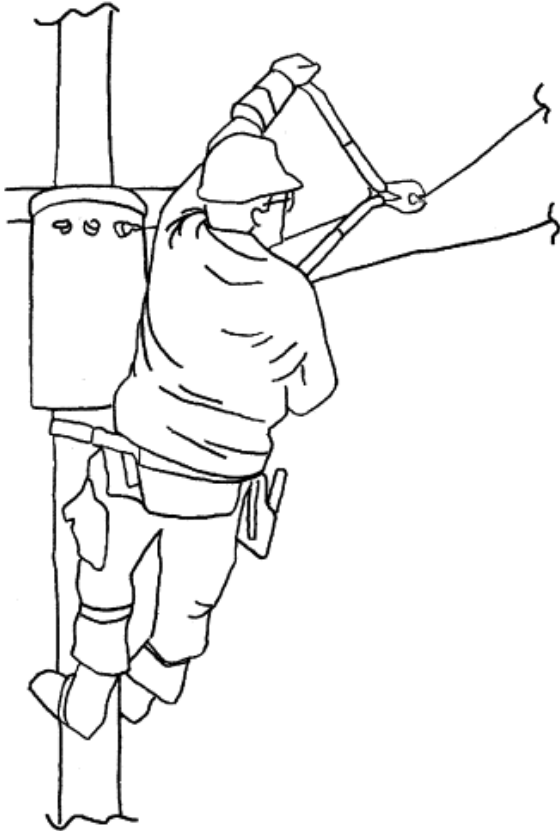
Fig. 4. An overhead line worker crimping a compression connector with a manual compression press from a pole. Courtesy of EPRI (December 2001).

One of the most common manual methods of cutting cable is with a long-handled, single pivot cutter. Fig. 5 illustrates an underground line worker cutting a cable with a common tool: a Thomas & Betts (Memphis, TN, USA) model #0390FCS manual cutter. The Thomas & Betts cutter has a single pivot mechanism, weighs 2 kg, has handles 61 cm long, and is rated to cut cable as thick as 4.5 cm diameter. Typical cable sizes that underground

line workers cut with a single pivot cutter are stranded aluminum 4/0 AWG (1.33 cm dia) and 500 MCM AWG (2.06 cm dia) (Kurtz et al., 1998). Line workers cut cables in a variety of postures in which one handle is supported by the body or ground and the other handle is pulled by both hands. One handle can be supported by the chest or armpit in a standing posture (Fig. 5), the iliac crest when the worker is in a crouched posture, or supported by the ground when the worker is in a flexed trunk posture. The number of cuts that an underground line worker makes in 1 day can be as many as 100 or more.

Fig. 5. An underground line worker cutting a wire with a manual cutter. Courtesy of EPRI (December 2001).

Symptom surveys from line workers and qualitative task evaluations conducted by the authors indicate that manual crimping of connectors and cutting cable are the tasks that pose the greatest risk of MSDs to line workers. A musculoskeletal survey of more than 150 active overhead line workers in the Midwest, Southeast, and Southwest regions of the US revealed that 40% of the respondents reported pain in their wrists, shoulders, or backs at least 1 day a week (EPRI, December 2001). Moreover, the most frequently cited cause for musculoskeletal pain in this survey was crimping connectors manually. Two risk factors for MSDs, high force and repetitive exertions, are requisite in the crimping and cutting tasks, and to the authors' knowledge the magnitude of the forces required to crimp connectors and cut cable are not known. Thus, the objectives of this laboratory study were first, to measure the forces applied to the handles of a manual press in order to connect common pairs of overhead wires, and second, to measure the forces applied to the handles of a manual cutter

to cut common underground gauges of cable. Quantitative results from this study could better enable health and safety professionals in the electric power industry to determine the extent to which crimping and cutting contribute to upper extremity MSDs and also establish a force benchmark to which alternative crimping tools and cutters can be compared.

2. Methods

2.1. Apparatus and procedure

2.1.1. Crimping connectors

An Instrom MTS (Instrom Engineering Corp., Canton, MA, USA) was used to measure the vertical force applied to the handles of a Burndy MD6 to crimp compression connectors. As shown in Fig. 6, two wires were inserted into a new compression connector, and the jaws of the manual press enclosed the connector in either the press' outer die or inner die (refer to Fig. 2). A portion of each handle was cut off and replaced with fixtures that were attached to the Instrom's drive cylinder on top and its load cell on the bottom. The location at which the drive cylinder and load cell were attached to the handles was close to the handles' ends, which is the recommended position for a worker to grasp the handles. The load cell on the bottom of the Instrom was rated for a full capacity of 44,500 N and was calibrated before testing. At the start of testing, the drive cylinder moved downward at a rate of 51 cm/min to close the two handles together, and thus make a complete crimp. Force vs. time data were plotted on a strip chart recorder throughout the duration of each crimp. The force vs. time data were collected from five replications of each experimental condition, and a new connector and wire were installed for each replication. Because the connectors required more than one crimp, the order of crimps on each connector was the center location followed by the right and left locations, respectively. If a connector required four crimps, then the left center position preceded the right center and the right and left outside locations followed, respectively. Two wire pairs and their required connectors were tested: 1/0 AA (all aluminum) AWG to ♯2 ACSR (aluminum conductor steel reinforced) AWG and ♯2 ACSR AWG to ♯6 Cu (copper) AWG. Diameters of the bare conductors of the 1/0 AA, ♯2 ACSR, and ♯6 Cu were 0.93, 0.81, and 0.41 cm, respectively (Kurtz et al., 1998). Electrical insulation added minimal thickness to the overall diameter of each wire.

Fig. 6. Instrom system applying vertical force to the handles of a manual press in order to crimp a connector. The drive cylinder is on the top, and the load cell is located at the bottom. Courtesy of EPRI (December 2001).

2.1.2. Cutting cable

Testing of cutting cable was performed with a Thomas & Betts cable cutter model # 0390FCS, and force vs. time data were collected in a similar fashion to the process for testing the manual press. Due to the 56 cm distance from the pivot point to the grasping location on the manual cutter's handle, the handles were shortened by 25 cm so the ends of the handles could fit within the full travel distance of the Instrom. Fixtures, which were mounted to the shortened ends of the manual cutter, were attached to the drive cylinder and load cell of the Instrom. The drive cylinder moved the shortened handles at a rate of 10 cm/min, which translated to a rate of 19 cm/min for the full-length handles (56 cm). Data were collected from the Instrom during five replications of each experimental condition. The forces applied to the ends of the shortened handles were denoted as the unadjusted forces. Then the unadjusted forces were multiplied by a coefficient to obtain the forces that would have been applied to the ends of the long handles of the manual cutter. These calculated forces were considered the adjusted forces. The peak adjusted force, which is the vertical force measured by the Instrom and adjusted to take into account the full length of the handle, was not modified to take into account changes in moment arm. Based on many observations of workers cutting cable, a worker typically applies a vertical force to the handle to cut cable and not a force that is perpendicular to the handle. Two typical sizes of underground cable were cut by the Instrom–4/0 AWG stranded aluminum and 500 MCM AWG stranded aluminum (1.33 and 2.06 cm dia, respectively). Electrical insulation added extra thickness to the overall diameter of each wire.

2.2. Experimental design

The crimping connector test had three independent variables: die location (outer and inner), crimp location (left, center, and right), and wire pair (1/0 AA to ♯2 ACSR and ♯2 ACSR to #6). The experimental design for the cutting test had one independent variable—cable size (4/0 and 500 MCM). The dependent variable for both experiments was the peak vertical compression force (N) applied to the handles of the respective tool.

2.3. Data conditioning and statistical analysis

The peak force for each crimping and cutting trial was read manually from the respective Instrom strip chart and recorded. For the cutting experiment, the adjusted force data and its time were recorded for each trial from the strip chart. Because the handles of the manual press and cutter were moving at constant speed in the Instrom machine, the time when the peak force occurred enabled the experimenter to determine the angle at which the peak force was exerted on the respective tool's handles. The time when the peak force occurred was converted to a percentage of the total time of the respective crimp or cutting movement, and this percentage was multiplied by the distance between the handles at the start of the trial to determine the distance between the handles when the Instrom exerted peak force.

The peak force data in the crimping connectors study were analyzed with two ANOVAs. First, the crimp location (left, center, and right) and die location (outer, inner) were analyzed with a two-factor ANOVA for each wire pair separately (1/0 AA to #2 ACSR and #2 ACSR to #6). Then the crimp location and wire pairs were analyzed with a two-factor ANOVA. The cutting cable study was analyzed with a one-factor ANOVA, testing whether there was a significant difference in peak force between the two cable sizes (4/0 and 500 MCM).

3. Results

3.1. Crimping connectors

Regarding the #2 ACSR to #6 Cu wire pair force data, which are displayed in Table 1 and Fig. 7, the peak force that was generated when the connector was pressed in the outer die location was greater than the inner die (mean values of 256 vs. 172 N, $p<0.001$). The crimp location also resulted in a main effect ($p<0.01$), and Duncan's post hoc testing indicated that the center (224 N) and left side (214 N) locations required more force than the right side (200 N). There was no interaction between crimp and die locations for connecting #2 ACSR to #6 Cu wires ($p>0.05$).

Table 1. Mean (s.d.) of peak vertical forces in N applied to the handles of the manual press as a function of die location and crimp location for the #2 ACSR to #6 Cu AWG wire pair (N=5)

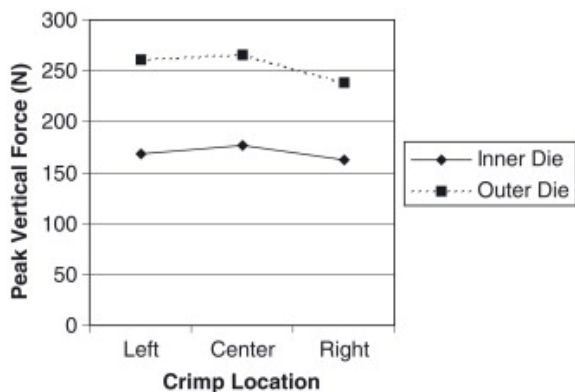|	Crimp location			Mean (s.d.) at die location
	Left	**Center**	**Right**	
Inner die	168N (5.4)	177 (6.2)	163 (6.5)	172 (8.5)
Outer die	261 (6.8)	266 (7.7)	238 (27.0)	256 (21.2)
Mean (s.d.) at crimp location	214 (49.3)	224 (46.9)	200 (41.7)	

Fig. 7. Means of peak vertical forces applied to the handles of the manual press as a function of die location and crimp location for the #2 ACSR to #6 Cu AWG wire pair.

Similar to the #2ACSR to #6 Cu wire pair data, the peak force data for the 1/0 AA to #2 ACSR wire pair showed a difference between the inner and outer die locations (mean values of 280 vs. 182 N, p<0.001). As indicated in Table 2 and Fig. 8, the location of the crimp significantly affected peak force values, with the two center locations (left and right center) requiring greater peak forces than both the left and right locations (mean values of 238–240 N for the two center positions vs. 224 N for the left and right locations, p<0.01). The right and left outside locations did not require different peak forces (p>0.05). There was no interaction in peak force between crimp and die locations for connecting 1/0 AA to #2 ACSR wires (p>0.05).

Table 2. Mean (s.d.) of peak vertical forces in N applied to the handles of the manual press as a function of die location and crimp location for the 1/0 AA to #2 ACSR AWG wire pair (N=5)

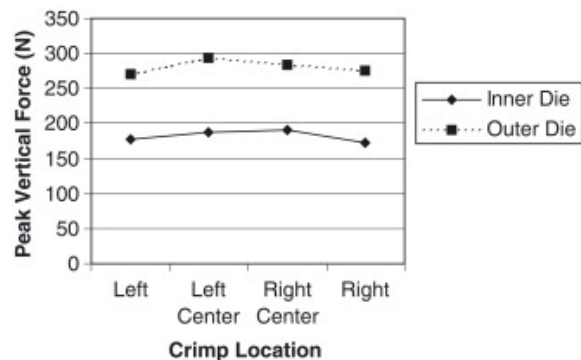|	Crimp location				Mean (s.d.) at die location
	Left	Left center	Right center	Right	
Inner die	177N (11.0)	187 (5.0)	191 (5.4)	172 (11.0)	182 (11.8)
Outer die	270 (16.1)	294 (8.9)	284 (12.5)	275 (11.8)	280 (15.1)
Mean (s.d.) at crimp location	224 (51.2)	240 (57.3)	238 (50.3)	224 (55.5)	

Fig. 8. Means of peak vertical forces applied to the handles of the manual press as a function of die location and crimp location for the 1/0 AA to #2 ACSR AWG wire pair.

Throughout its full travel in the Instrom, the Burndy MD6 resulted in peak force for both wire pairs when the handles were separated at approximately 34° (Wilzbacher, 2002). The angle between the handles started at approximately 70°. In addition, ANOVA revealed that there was no difference in peak forces required to crimp 1/0 AA to #2 ACSR and #2 ACSR to #6 Cu (p>0.05).

3.2. Cutting cable

The peak forces differed for cutting 4/0 and 500 MCM cables with the Thomas & Betts manual cutter, as evinced by mean values of 227 N (s.d. 6.2) and 503 N (s.d. 18.2), respectively (p<0.001). These forces were derived by multiplying the vertical forces directly measured from the Instrom on a shortened handle by a coefficient to determine the peak vertical forces applied to the long handles of the manual cutter. When peak force occurred throughout a cutting stroke, the angle between the handles of the manual cutter averaged 44° for the 4/0 cable and 29° for the 500 MCM cable.

4. Discussion

This study demonstrates that peak forces required to press typical overhead connectors and cut common underground cable are very large and restrict the percentage of the general population who are capable of

doing line work. Crimping a compression connector just once requires almost 300 N of force, and based on a database of maximum isometric shoulder strength (Stobbe, 1982), less than 1% of men and women from industry have the shoulder strength to make one crimp connecting 1/0 to #2 wire. This calculation is based on a peak force of 294 N (from Table 2) applied downward (shoulder adduction) at a distance of 41 cm from the center of the shoulder complex when the shoulder is elevated 90°. This shoulder posture and direction of force resemble a typical posture of the raised arm of an overhead line worker making a compression connection with a manual press from either a bucket or pole (refer to Fig. 3, Fig. 4).

Cutting a 500 MCM cable (2.06 cm diameter) with a manual cutter requires an average force of 503 N applied to the handles. One common approach to cutting 500 MCM cable is to place one handle in an armpit cradle (right armpit for right-hand dominant workers) and place the other handle in front of the armpit and then pull the handle in front of the armpit with both hands towards the armpit. The peak force of 503 N occurs when the handles are separated at approximately 30 cm. Van Cott and Kinkade (1972) reported maximum pull strength from 15 male subjects pulling on an aircraft control stick placed close to the position where the manual cutter's handle requires maximum force. Van Cott and Kinkade found that the average pull strength among the 15 subjects was 534 N, which indicates that approximately 50% of males have the upper extremity strength to cut the 500 MCM cable. However, if the magnitude of peak pull force to cut the 500 MCM cable (503 N) and position of the hands and arms are modeled with the University of Michigan 3-D Static Strength Prediction Program (SSPP), less than 1% of females from the general population have the elbow and shoulder strength to cut 500 MCM cable with a manual cutter. Less than 40% and 60% of males have the maximum elbow and shoulder strength, respectively, to cut the 500 MCM cable with a manual cutter, based on 3-D SSPP calculations. Therefore, there is good agreement between the results obtained from 3-D SSPP (40–60%) and Van Cott and Kinkade (1972) (50%) for the male population having the upper extremity strength to cut cable.

The very large external forces required to crimp connectors and cut cable manually indicate, first, that only a small, select group of people can perform line work, and second, that the magnitude of forces required to perform line work can expose line workers to the risk of MSDs, particularly the upper extremity. The fact that a worker may have the maximum strength to manually connect 1/0 AA to #2 ACSR wire or cut cable up to 2 cm diameter does not mean that the worker is free of MSD risk. Line workers sometimes are required to make connections or cut cable up to 100 times or more per day. The high number of repetitions, coupled with extremely large forces, can place high tensile loads on the tendons and bursa in the shoulder complex. If these structures become irritated, inflammation of the tendons and bursa could occur, possibly resulting in joint pain and a cascade of reactions. The possible consequences are reduced joint mobility, decreased muscle strength, diminished tendon travel, and nerve entrapment (Chaffin et al., 1999). Examples of shoulder MSDs are supraspinatus tendinitis (also called rotator cuff tendonitis or impingement syndrome), rotator cuff tears, bicipital tendinitis, and bursitis (Millender et al., 1992).

Loading on the shoulder tendons and bursa is further exacerbated by the abducted or flexed posture of the shoulders that is required to crimp connectors and cut cable manually. In a review of the literature, Hagberg et al. (1995) reported welders and assemblers, who often abduct or flex their shoulders at work, had greater prevalence of shoulder MSDs than control groups. Elevated shoulder posture is a third risk factor, in addition to force and repetition, that exposes line workers to shoulder MSDs when they crimp connectors and cut cable manually (Sakakibara et al., 1995).

Similar to the harmful consequences from inflammation of tendons and bursa in the shoulder complex, high tensile load on the muscles of the shoulder complex can also cause muscle fatigue and ischemia (Chaffin et al., 1999). The repetitive nature of crimping connectors and cutting cable can fatigue the shoulder muscles very quickly. If a muscle were exerting 90% of its maximum strength (%MVC) in a sustained contraction, then the

average time that the muscle could sustain that contraction is 20 s (Van Dieen and Oude Vrielink, 1994). For some workers, repeatedly pressing compression connectors or cutting cable manually could result in %MVC approaching or exceeding 90% MVC and thus muscle fatigue. Severe levels of muscle fatigue could possibly lead to muscle spasms and limitations on functional ability, such as diminished joint range of motion.

An alternative to the manual methods of pressing connectors and cutting cable are battery-operated tools that enable a worker to press compression connectors and cut cable up to 750 MCM (2.5 cm dia). A worker holds the cordless tool with one hand and then squeezes the trigger with the other hand; in some applications, a worker can use a battery-powered tool to press or cut with only one hand. Battery-powered presses and cutters for typical overhead and underground pressing and cutting tasks are relatively lightweight (less than 7 kg) and are easy to maneuver. However, they cost about $2000 or more each, which is at least six times greater than manual tools. Hence, many utilities have been reluctant to purchase battery-powered tools to replace manual tools. A chapter in the EPRI (December 2001) handbook addressing overhead workers' ergonomics found that the payback period for purchasing battery-powered presses to replace the manual presses was less than 1 year. Although some utilities do use battery-powered presses, many utilities still use manual presses and cutters for overhead and underground tasks.

Supplanting manual presses and cutters with battery-powered tools requires management commitment to ergonomics. After the payback period for justifying battery-powered presses was published in the EPRI handbook (December 2001) (and was later published in Seeley and Marklin, 2003), senior management at We Energies, a medium-sized utility in the upper Midwest of the US, agreed in 2002 to purchase battery-powered presses and cutters for all their overhead line crews (approximately 100) and battery-powered cutters for all their troublemen (those workers who are the first to investigate emergency calls, approximately 100). The price for all the battery-powered tools purchased in 2002 was $1.3 million. In 2003, We Energies purchased an additional $150,000 for battery-powered presses for the troublemen and has a long-range plan to replace all manual presses and cutters in their storerooms with battery-operated tools. (The tools in the storerooms are used primarily for emergencies such as storm outages.) Manufacturers of battery-powered tools are continually improving the technology of their tools, and line workers from the We Energies ergonomics team provide input to manufacturers on how the tools perform in the field and can be improved.

The purchase of battery-powered tools by We Energies has made a great impact on the affected workers, both physically and psychosocially, and demonstrated to the workers that senior management was committed to sustaining the work of the overhead line workers' ergonomics team. Without the support of ergonomics by senior management at We Energies, the battery-powered presses would not have been purchased and the impact of the overhead line workers' ergonomics team would have been limited. In a previous ergonomics intervention study funded by the National Institute for Occupational Safety and Health (NIOSH, 1994) at three meatpacking plants, two ergonomics teams were formed at one of the meatpacking plants. The two teams, which were composed of mostly production workers, were guided by an outside ergonomics researcher for over 9 months. When the formal involvement from the researcher ended (because the NIOSH grant expired), the ergonomics initiatives generated by the teams died because management was not committed to the sustenance of the two teams. One lesson learned from the NIOSH study was that top management commitment and support were essential for ergonomics teams to implement their recommendations (NIOSH, 1994), which often are in the form of new tools or equipment.

While battery-powered presses and cutters are preferred to the current manual tools, improved designs of manual tools that cost less than battery-powered tools and reduce handle forces substantially may persuade some utilities to replace their current manual tools with improved manual tools. Manufacturers of manual presses and cutters could use the methodology described in this article to test new designs and quantitatively determine their primary benefit, i.e. the reduction in peak handle forces. The decreased handle forces from new

designs could be fed into strength databases and models, such as the 3-D SSPP, in order to determine the percentage of the general population who have the strength to perform the tasks and also estimate the reduction in risk of MSDs to workers. In addition, the methodology presented in this article could be applied to other manual tools that compress connectors or cut wire or cable.

Acknowledgements

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