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ROBOT-RELATED FATALITY INVOLVING A U.S. MANUFACTURING PLANT EMPLOYEE: CASE REPORT AND RECOMMENDATIONS

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ABSTRACT*

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This article presents the salient characteristics of the first publicly documented robot-related fatality in the United States and summarizes recommendations for both preventing similar accidents and directing future robotic safety research and practice. In July of 1984, a 34-year-old die cast operator with 15 years experience was pinned between the right rear end of a hydraulic robot and a "safety pole". This operator was one of approximately 66 operators employed by the die cast company and was considered by many to be among the most adept at working with the plant's two robots. The major factor contributing to the death of this worker may have been his own behavior; he had been formally trained and instructed not to enter the envelope while the robot was operational. This American fatality has several characteristics in common with reported Japanese robot fatalities. These characteristics include: experience, entering the robot range of motion with power on, overriding existing safety systems, being struck from behind, and being pinned or crushed at a pinch point between the robot and stationary equipment. Recommendations for prevention of such injuries are made according to broad categories pertaining to ergonomics, training, and supervision. Specific recommendations for future robotic safety research and practice include improving information dissemination and consultation, addressing psychological factors of workers interacting with robots, assessing the effectiveness and limitations of safeguarding, establishing uniform and objective criteria for training and possibly certification, and expanding scientific research to include better surveillance and epidemiologic and ergonomic studies.

INTRODUCTION

Although fatal robot-related accidents have been documented in Japan (Anonymous, 1982), the first publicly documented case in the United States occurred in July, 1984. The die cast company has approximately 280

*Mention of company name or product does not represent NIOSH endorsement.

employees (including 66 die cast operators) and 24 die cast machines. During the two years prior to this accident, four robots were purchased and two were placed into production. The company works three shifts and operates 24 hours a day. Prior to the accident, the employees had been working six days (and occasionally seven days) a week. A 34-year-old die cast operator with 15 years experience went into cardio-pulmonary arrest after being pinned between the right rear end of a rotating hydraulic robot and a safety pole. He was admitted to the local hospital where, five days later, he was pronounced dead as a result of cerebral necrosis. This case was evaluated by the National Institute for Occupational Safety and Health (NIOSH) Division of Safety Research (DSR) as part of its Fatal Accident Circumstances and Epidemiology (FACE) Project. The objectives of this article are to summarize causative factors associated with this accident and present recommendations for both the prevention of similar accidents and directions for robotic safety research.

REVIEW OF THE LITERATURE

According to the Robot Institute of America (RIA) " a robot is a reprogrammable multi-functional manipulator designed to move material, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks". As with the introduction of any new technology, there is the potential for the introduction of new risks into the workplace. Existing literature shows that robots pose some safety hazards which are not characteristic of machinery in general. Robots have movable parts (arms) which possess large amounts of kinetic energy, move automatically, and are not intrinsically surrounded by a protective casing (Noro and Okada, 1983). Furthermore, workers may perceive robots as something more than machines, and therefore may exhibit greater attraction to and personalization of robots (Courter, 1985). Both the anticipated accelerated usage and human-like qualities of robots suggest needed concern for worker safety.

Regardless of the type of robot involved, two safety premises are expounded in the literature. The first premise is that the introduction of robots into the workplace increases the safety of workers. By using robots to replace workers who are in hazardous environments, human exposure to associated deleterious tasks and conditions may be reduced. However, existing literature does not include scientific data which quantify the degree to which worker safety is increased through use of robots to perform tasks previously accomplished by workers. The second premise concerns prioritization of safety concerns with respect to workers, robots, and other machines. A tremendous amount of research has enhanced the sophistication of robotic technology with respect to accuracy, repeatability and reliability. Furthermore, technology has enhanced the dependability of robots so that "downtime" and the likelihood of equipment damage are minimized. However, considerably less effort and attention have been focused on worker safety.

Published descriptions of robot-related injuries are limited. Four fatal cases which occurred in Japan have been described (Altamuro, 1983). The first case involved a repairman who climbed over a safety fence while a robot was operational. The robot pushed him into a grinding machine, which resulted in death. The second case occurred when a worker climbed over a conveyor to remove a defective part and the robot squeezed the worker to death. A third worker was killed when he stepped between a stationary industrial planer and a robot. He reactivated the robot before being completely out of the way and the robot crushed him against the machine. The fourth fatality occurred when one worker started a welding robot while another unsuspecting worker was still within its work envelope. The robot pushed the man into the positioning fixture, which resulted in the death of the worker.

Similarly, an important factor in 18 robot accidents in Japan, which resulted in injury, was performance of unauthorized entrance into the robot envelope (Sugimoto, 1977). In a case series of 36 robot accidents resulting in injury to Swedish workers, 28 involved a robot that manipulated parts (Carlsson, 1984). Furthermore, 14 occurred during normal operation of the robot, while 15 occurred during repairing, programming, or setting up the robot. The average ratio of accidents to robots in Sweden during 1977 was one accident for every 40 robots (Carlsson et al., 1983). In the United States, one automotive corporation experienced 16 non-fatal robot accidents during approximately $2\frac{1}{2}$ years of robot usage (Minter, 1984). It is estimated that this same automotive company may have over 21,000 robots by 1990 (Minter, 1984). Similar accelerations in robot usage by other large U.S. automotive companies are anticipated.

METHODS

The NIOSH Fatal Accident Circumstances and Epidemiology (FACE) Project utilizes several different sources to gain notification of selected occupational injury fatalities. One of these sources is the Consumer Product Safety Commission's Medical Examiner and Coroner Alert Project (MECAP). The MECAP entails the voluntary reporting of product-related deaths. Those cases which are of an occupational etiology are shared with NIOSH. The robot-related fatality was reported through the MECAP by the attending county coroner.

After the decision was made to include this case in the FACE Project, telephone contacts were made with representatives of the employer (the company president and director of manufacturing) and officials of the state's Department of Labor who are responsible for the enforcement of occupational safety and health regulations. Although state officials had already conducted an investigation of this fatal accident, FACE Project representatives stressed the research orientation of their proposed field evaluation. The completed field evaluation and this article would not have been possible without the voluntary cooperation of the employer and the invaluable assistance of state officials.

Approximately one month after the accident occurred, a NIOSH team consisting of an epidemiologist, a mechanical engineer, and a safety engineer conducted the field evaluation. An opening conference was held with the company's director of manufacturing who provided background information about the company's history, production, safety and training programs, injury statistics, and use of robots. The NIOSH team conducted a site survey, which included visual observation and photographic documentation of both the accident site and another automated die cast system. During the site survey, interviews were held with the director of manufacturing and several operators in order to better comprehend the events surrounding the accident and the daily activities performed by the operators. Other interviews were held with the operator who first found the victim, the foreman who was on duty the day of the accident, the president of the local union, the county coroner, members of the emergency medical squad, members of the fire department medical squad, and the city dispatcher.

RESULTS

On Saturday, July 21, the victim was working with an automated die cast system that utilized a materials handling robot. Management and co-workers described this worker as being very adept and experienced at operating this system. The robot was programmed to extract the casting from the die cast machine, dip it into a quench tank, and then insert it into an automatic trim press (Fig. 1). The robot was programmed to perform the entire 27 step cycle in approximately 1 min. The robot's safeguarding system included two horizontal safety rails with an interlocking gate, and a "safety pole" intended to prevent erratic arm movement.

At approximately 1:00 p.m., the victim entered the work envelope of the robot by either climbing over or through the safety rail, or by walking through one of the unguarded gaps between the safety rail and die casting equipment (See Fig. 1). There was a 32-in wide opening between the interlocking gate and the die cast machine, and a 19-in wide gap between the other end of the railing and the automatic trim press. Why the worker entered the robot's work envelope is uncertain. Several co-workers believed that since he had an air hose with him, he may have been trying to clean up "flash" and "scrap metal" that had accumulated on the floor. The air hose was attached outside the work envelope but was sufficiently long to allow the operator to clean up the floor anywhere inside the envelope. Fellow workers also stated that they had seen this operator inside the envelope on previous occasions when the robot was operating, although he had been warned against this prohibited activity during the robot manufacturer's

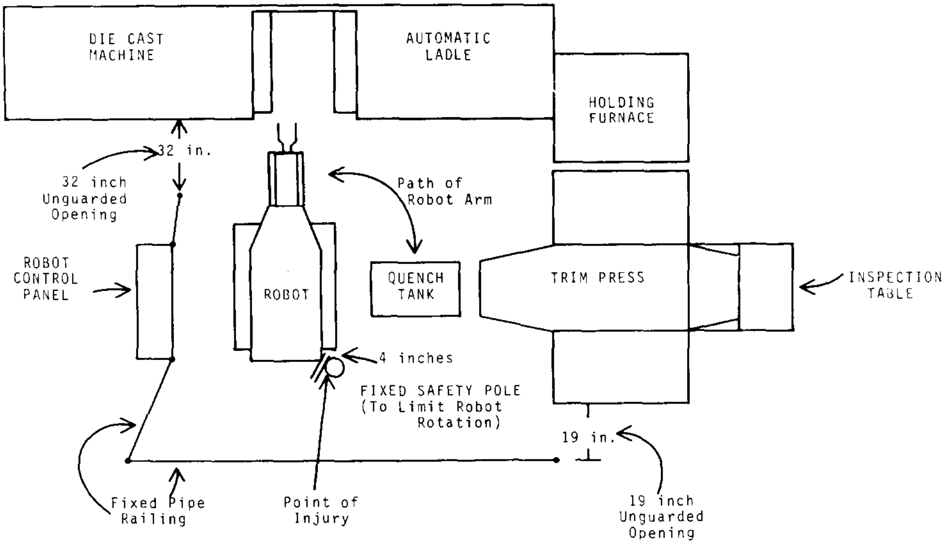

Fig. 1. Diagram of the work station where the robot-related accident took place.

training course which he attended from June 25, 1984 through July 1, 1984.

The victim was discovered by the operator of the adjacent die cast machine. Although the accident site was not directly observable from the neighboring work station, the operator stated that he became curious when he heard the steady hissing of the air hose for 10—15 min. When he investigated the noise, he found the victim pinned between the right rear of the robot and a "safety pole" in a slumped but upright position (Fig. 2). The robot stalled when it pinned the man's body; however, it continued to apply pressure on his chest.

When the director of manufacturing arrived on the scene, co-workers were attempting to unpin the victim with a hand-held teach pendant which is connected to the robot's controller. The teach pendant is a hand-held device which is used to program the robot. After several unsuccessful attempts with the teach pendant, a second teach pendant was brought from another robot. Using this pendant, the director of manufacturing finally unpinned the victim and CPR was immediately administered. The fire department arrived approximately one min later. The emergency medical service arrived approximately two min after the fire department, and transported the victim to the local hospital. The victim was pronounced dead five days later. The complete pathology of the injuries was unknown since the family did not grant permission for an autopsy. However, the county coroner stated that there were no macroscopic signs of crushing injuries, and X-rays of bones and internal organs were negative. Subsequent to the accident, the

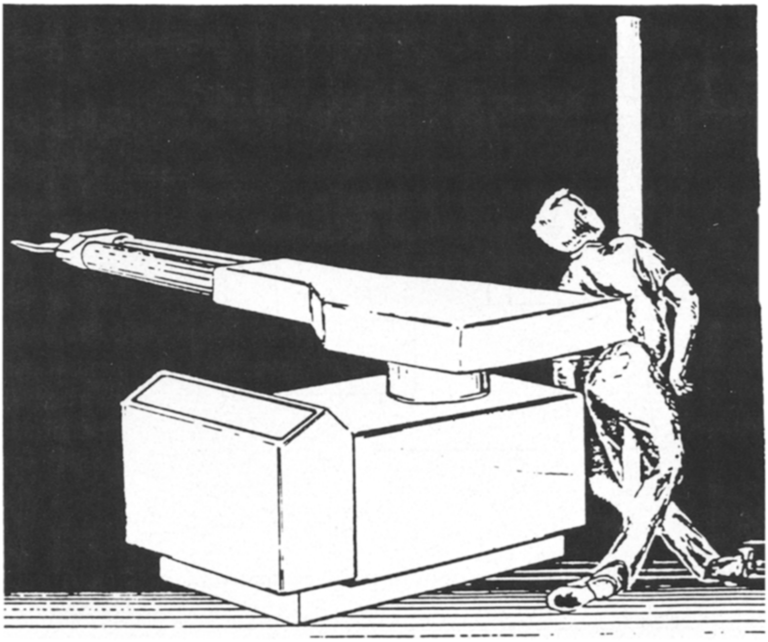

Fig. 2. Artist's rendition of the body position of the operator while pinned by the robot arm.

company replaced the safety rails with a cyclone fence which covered the gaps and made unauthorized entry more difficult.

The information obtained from the field evaluation allowed NIOSH researchers to address selected safety issues associated with the occurrence of this accident. The victim was an experienced die cast operator who had recently been trained in the robot manufacturer's one week training course and also received on-the-job instruction. This training warned operators against the practice of entering the envelope while the robot is operating automatically. Furthermore, the victim had been both previously observed and verbally warned by fellow employees against entering the work envelope during automatic operation. The major factor contributing to this fatal accident may have been the victim's behavior.

The results of the field evaluation were also used to formulate general safety recommendations which may be applicable to many establishments who use or anticipate using robots. These recommendations may be grouped in broad categories pertaining to ergonomic design, training, and supervision.

With reference to *ergonomic design*, safety fencing with interlocking gates is more effective than rails for preventing unauthorized entry and should completely enclose the robot work station. Rails will not necessarily prevent intentional entry. The system should be designed such that the robot's main control panel and associated equipment control panels are located outside of the robot's work envelope. Safety posts, designed to restrict the movement of the robot's arm in case of "loss of control", should not be used. Since this accident involved a hazard (the pinch point created by the rear end of the robot and the "safety pole") perceived neither by the victim nor by management, it may be helpful to paint the robot's full range of motion on the floor. Finally, in the design of robotic work stations, consideration should be given to visibility of human tasks so that supervisors may better manage workers and co-workers can better recognize emergency situations.

With reference to *training*, extensive instruction should be provided for all employees who will be programming, operating, or maintaining robots. This training should focus upon safety as well as methods of programming, starting, and stopping robots. Any training program should familiarize trainees with all working aspects of the robot, including full range of motion, known hazards, how the robot is programmed, emergency stop buttons, and safety barriers, before operating the robot or performing maintenance at a robotic work station. The following general procedures should be used:

- Operators should never be in the work envelope while the robot is functioning automatically.
- Since programming may have to be done inside the work envelope while the robot is operational, programmers should operate the robot at a slow safe speed and be aware of all possible pinch points.
- Training is not only needed for the inexperienced workers but refresher courses should be provided for experienced programmers, operators, and maintenance workers.

With reference to *supervision*, enforcement of a set of clearly written safety rules, which are specific to robotics, is strongly recommended to ensure the safety of workers. Newly trained employees may require close supervision until they are familiar with the robot system. Strict enforcement of the rules with appropriate corrective action should be considered against anyone who enters the work envelope without first putting the robot in a "power down" condition. Supervisors should be cognizant of the fact that operators experienced at automated tasks may become bored, overconfident, or lose concern for their own safety. These conditions may increase the worker's risk of injury.

DISCUSSION

This fatal-related accident was several characteristics in common with the four reported fatal accidents in Japan. One, the victims were experienced and trained in robotic operations and safety. Two, the victims entered the work envelopes of the robots in order to personally rectify perceived problems. Three, the victims inadvertently or willfully violated existing safety measures. Four, the victims were struck from behind by the robot. Five, the robots pushed or crushed the workers against another piece of equipment. Although based upon five cases only, these similarities are striking and may clearly predict the circumstances of future robot-related fatalities. These similarities may be effectively used to guide further safety research and practice concerning lethal exposures to robots.

Ironically, this fatality did not occur in an automotive plant where most robots are used, but in a small automotive-support industry, which purchased a used robot to automate its production. This robot-related fatality may serve to illustrate a very important present and/or future need of certain companies. Large employers with extensive robotics applications are likely to have the resources to ensure proper safety considerations in the set-up and use of robotics. However, smaller companies with limited resources may be more likely to buy used robots, retrofit existing work stations to accommodate them, and place limited emphasis on written safety procedures and enforcement. Efforts should be made by robot manufacturers to serve as consultants to employers who need assistance with the safe implementation and/or usage of robotics. The insufficient dissemination of existing information pertaining to robotic safety would then be minimized.

It appears plausible that workers, whose jobs become less physically intense due to automation, may become bored and find themselves attempting to create work. Another potential concern about the psychological impact of robots on workers is the attitudes they may form while working with robots. Since some workers may spend more time with robots than with other workers and may perceive robots to be something more than machines, there may be a tendency to personalize robots. (For example, the victim had nicknamed his robot, "Robby".) This personalization may cause the worker's mind to be more focused upon the "teamwork" with the robot rather than upon relevant safety issues.

This fatal accident demonstrates one possible problem with the safeguarding of robot workstations. The conscientious use of safety devices may not always have the desired effect and may, in fact, present new hazards. This problem can arise when robotic work stations purchased with no safeguards are retrofitted. In this case, a steel "safety pole" was installed in order to eliminate the hazard associated with erratic movement of the robot's arm. However, this safety control presented a new safety hazard by creating a lethal pinch point.

The pinch point was lethal due to the operational behavior of the robot. After pinning the operator, the robot applied continual pressure to the chest of the operator as it tried to finish executing its programmed path of motion. Possible solutions include software subroutines which would reverse robot motion when an obstruction is encountered. One United States robot manufacturer has developed a collision detection system which reverses robot motion when it detects an unexpected obstruction.

Existing robot-related safety hazards may be exacerbated by the increasing utilization of robots. One factor, which might slow the growth of robotics and the need for specifically directed safety efforts, would be worker resistance to this technology. In the evaluation of this fatal accident, however, NIOSH researchers were able to observe, firsthand, the belief by both individual workers and union representatives that robots are an absolute necessity for sustaining quality product output and competitiveness with foreign manufacturers. Furthermore, workers appeared eager to learn about and operate robots. These same worker attitudes have been observed in the United Kingdom (Inbucon, 1981).

This evaluation of the first publicly documented robot-related fatality in the United States does not represent DSR's only initiative in robotic safety. Currently, a robot-related accident surveillance program is being established with the collaboration of state and federal OSHA programs. Research is being sponsored that will develop a three-level electronic robot safety sensor system that detects human intrusion into the robot's working range. This system will consist of a light curtain, a pressure sensitive mat, and an ultrasonic sensor. The DSR is also coordinating research with France's National Institute for Research and Safety by collecting data which will lead to the development of safe procedures for performing maintenance on industrial robots and automated systems.

The management of companies which use robots should give consideration to the type and degree of safeguarding used to minimize risk of injury to employees who work with or around robots. As stated in the "Proposed American National Standard for Robots and Robot Systems" (Robotic Industries Association, 1984), the means and degree of safeguarding should correspond directly to the type and level of hazard presented by the robot system. Perimeter safeguarding can be accomplished with varying levels of protection. Chains, ropes, railings, and line markings on the floor only serve to provide a warning rather than prevent unauthorized entry. But if a greater degree of hazard is present, a six-foot high chain link fence with an interlocking gate may be necessary to prevent unauthorized entry into the robot's work envelope. Specific robot applications may disseminate fumes, liquids, or foams of high toxicity. Perimeter safeguarding for these types of robot installations may require plexiglass or a similar non-porous enclosure with an interlocked accessway. However, the use of barrier guarding should not be viewed as a panacea for robot safety hazards. Employees may, on occasion, climb over fences rather than go through interlocking gates. The current trend in some European countries is to use less guarding (Edwards, 1984). This is being done in order to avoid creating a false sense of security and to develop self-discipline among workers who interact with robots.

The education, training, and certification of programmers, operators, and maintenance workers have been discussed in some robotic safety circles. Education and training appear less controversial than certification because most people recognize the need to be aware of and familiar with associated hazards of the robot systems to which they are exposed. If certification is to become a viable safety strategy, aspects pertaining to training criteria, types of workers who should be certified, and when they should be certified must be objectively determined.

Future research considerations are important. Accurate enumeration of both robots and associated worker injuries and deaths through comprehensive surveillance systems is essential. Consequently, for the success of any surveillance effort, it will be necessary for manufacturers, users, safety practitioners, trade and safety associations, and government agencies to adopt a universal definition of a robot. Surveillance activities should also quantify the numbers and types of workers who work around or with robots. It is certainly difficult to estimate the reduction of accidents and injuries due to the replacement of workers by robots. Yet, speculation is the only available gauge used to estimate increased safety. Epidemiologic methods should be used to document the magnitude of change in injury risk resulting from the replacement of humans with robots in hazardous work environments, as well as the relative efficacies of various preventive control strategies. The "Proposed American National Standard for Robots and Robot Systems" states that "all robots capable of hazardous motion, shall have a slow speed" (Robotic Industries Association, 1984). With the development of robots that are capable of extremely high speeds, a slow speed mode will be essential for workers who perform programming or maintenance tasks in close proximity to robots. Currently no experimental determination has been made of what constitutes a safe slow speed. Research should scientifically identify a speed for robot manipulators that takes into account workers' ability to recognize and react to unexpected robot movements.

In conclusion, the American fatality and four Japanese fatalities clearly demonstrate the need for research and application of recommendations and practices to reduce injuries from robots in the workplace. Research and dissemination of information on psychological factors, safeguarding, education and training, and surveillance of near-miss accidents, are needed to better understand these factors and to ascertain their effectiveness in preventing future robot-related injuries and fatalities.

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