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Case Studies of Robots and Automation as Health/Safety Interventions in Small Manufacturing Enterprises

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Abstract

This paper reviews the experiences of 63 case studies of small businesses (< 250 employees) with manufacturing automation equipment acquired through a health/safety intervention grant program. The review scope included equipment technologies classified as industrial robots (n = 17), computer numerical control (CNC) machining (n = 29), or other programmable automation systems (n = 17). Descriptions of workers' compensation (WC) claim injuries and identified risk factors that motivated acquisition of the equipment were extracted from grant applications. Other aspects of the employer experiences, including qualitative and quantitative assessment of effects on risk factors for musculoskeletal disorders (MSD), effects on productivity, and employee acceptance of the intervention were summarized from the case study reports. Case studies associated with a combination of large reduction in risk factors, lower cost per affected employee, and reported increases in productivity were: CNC stone cutting system, CNC/vertical machining system, automated system for bottling, CNC/routing system for plastics products manufacturing, and a CNC/Cutting system for vinyl/carpet. Six case studies of industrial robots reported quantitative reductions in MSD risk factors in these diverse manufacturing industries: Snack Foods; Photographic Film, Paper, Plate, and Chemical; Machine Shops; Leather Good and Allied Products; Plastic Products; and Iron and Steel Forging. This review of health/safety intervention case studies indicates that advanced (programmable) manufacturing automation, including industrial robots, reduced workplace musculoskeletal risk factors and improved process productivity in most cases.

Keywords

robot; manufacturing automation; musculoskeletal disorders; intervention; case studies

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1. INTRODUCTION

This paper reports a retrospective review of case studies of automation implemented by small manufacturing industry employers as interventions to improve health/safety experiences in their workplaces. The study was motivated by interest in the use of industrial robots and other forms of more advanced programmable automation in mitigating workplace hazards and improving safety and health. The unique data source comes from the Ohio Bureau of Workers' Compensation (OHBWC) Safety Intervention Grant (SIG) program, an insurer-supported grant program that provides a subsidy to incentivize employers to implement equipment interventions to improve safety and health in their workplaces (Wurzelbacher et al, 2014; Miller et al, 2017). A requirement of the SIG program is that grant awardees (employers) submit a follow-up case study report at least one year after the award to describe experiences with the intervention equipment. In previous work we reviewed case studies reporting on the intervention equipment purchased by Construction industry employers through the SIG program (Lowe et al, 2020). The present analysis has a focus on advanced (programmable) automation equipment implemented by employer grant awardees in manufacturing industries.

The business case for robotics and other industrial automation typically emphasizes benefits on production cost, performance, and sustainability (Ogbemhe et al, 2017; Makris et al, 2017). From the standpoint of workplace safety, there are dual perspectives on robots and advanced forms of automation. These technologies have been associated with the causes of some catastrophic injuries, though current analyses with Census of Fatal Occupational Injuries (CFOI) data suggests a low prevalence of fatal injuries involving robots between the years 1992 – 2017 (Layne, personal communication). Alternatively, the positive health/safety perspective recognizes that robotic technologies can mitigate exposures and physical demands on human workers (Makris et.al, 2017, Thomas et.al, 2016) and the benefits of removing human workers from taking on the so-called "dirty, dull, and dangerous" tasks (Takayama et al, 2008). A 2001 Department of Energy (DOE) review of 68 new technology deployments at DOE facilities found that 71% exhibited a moderate to high potential of reducing occupational exposures even though only one was implemented with the *primary* objective of worker well-being (Boyd et al, 2001). Positive impact on workplace health/safety is often credited as a (desirable) secondary outcome of new technologies. In the OHBWC SIG program, however, a main objective of the intervention should be to improve employee health/safety.

The potential for industrial robots and automation to mitigate workplace hazards and prevent injuries has been described in a variety of industry trade articles (e.g. Whitton, 2020). We are not aware of a large collection of case studies of employer experiences with health/safety interventions, like that of the OHBWC SIG program, collected in a generally structured and consistent manner (Miller et al, 2017). Details of the SIG program are described in previous publications of these data (Wurzelbacher et al, 2014; Wurzelbacher et al, 2020; Lowe et al, 2020). The key element of the Ohio SIG program is that awardees receive matching funds as a multiple of 2:1, 3:1, or 4:1 of their initial investment for the purchase of equipment expected to positively affect employee safety/health and that the funds matching total is capped at $40,000 per grant award (nominal US dollars). A second key element is the requirement that grant awardee employers submit a final report describing the experience with the intervention equipment after one and/or two years of its implementation.

This paper summarizes the experiences of employers receiving Ohio Safety Intervention Grants to implement industrial robots and other advanced programmable manufacturing automation for the primary purpose of improving employee safety and health. Specifically, we looked to identify the types of compensable injuries and physical risk factors that were present in the work processes in which these technologies were implemented. We sought to describe the employer organization's experience with the equipment, considering safety and health risk factor outcomes primarily and productivity outcome secondarily. As with many types of workplace equipment that reflect larger capital investments and affect multiple employees, these technologies are generally infeasible to evaluate through randomized controlled trials (RCTs) and more robust experimental design studies with sufficient statistical power to detect differences across low prevalence outcomes. Thus, individual case studies provide weaker evidence than that of RCTs and experimental design studies for establishing intervention efficacy. However, case studies are feasible to conduct, and the OHBWC SIG program has amassed many case studies of interventions, some of which were known to include manufacturing automation equipment and industrial robots.

2. METHOD

2.1 Data Source and Case Study Search

A database of approximately 2,600 awarded SIGs (grants awarded in years 2003–2017) and descriptions of the equipment purchased was provided to the investigators by OHBWC in 2018. The provided SIG program documentation submitted by employers spanned this same time period. Case studies included the documentation of the employer grant awardee's original grant application and corresponding final report describing the intervention equipment experience. This was a secondary analysis, and the authors had no interaction with these employer organizations or any of their employees. No individual data from employees were collected or analyzed by the investigators.

The OHBWC SIG database classifies employers using an insurance system occupation/ industry coding that can be equated (i.e. cross walked) to codes of the North American Industry Classification System (NAICS). However, restriction within the NAICS Manufacturing Industry codes was found to be inadequate to capture all intervention equipment and use cases of interest. Several employer establishments classified to non-Manufacturing industry codes received grants for manufacturing automation equipment. An example is an employer classified as a non-residential framing contractor who acquired a three-axis, fully automatic structural steel punching, marking, and shearing system to reduce MSD risk factors from the holding and manual manipulation (pushing/ pulling) of the steel material and risk factors for "numerous first aid injuries, such as pinched fingers, cuts, etc." in their fixed site metal fabrication shop. Equipment-purchased description fields were reviewed manually for all employers in the Manufacturing Industry NAICS codes by screening that field for equipment that might meet the review inclusion criteria. Grant awardees in all other non-Manufacturing industries were searched using a controlled vocabulary within the equipment-purchased text description field. A broadly inclusive syntax was applied using the terms: Auto*, CAD (computer aided design), CAM (computer aided manufacturing), CAE (computer aided engineering), CNC (computer numerical control), Comput*, Control*, Detect*, Index*, Process*, Program*, Robot*, Sensor*. We defined a broad scope to include industrial robots and other types of advanced (programmable) automation equipment. The identification of *industrial robots* was based on the ISO 10218/ANSI R15.06 definition: "…an automatically controlled, reprogrammable, multipurpose manipulator programmable in three or more axes, which may be either fixed in place or mobile for use in industrial automation applications." The broad scope included the key criterion that the equipment incorporated programmable automation in a manufacturing process.

2.2 Data Extraction

A basic entry template was created in Microsoft Excel for direct input of quantitative data for date of grant award, count of employees affected by the pre-intervention process, equipment purchase costs (employer contribution plus grant subsidy), quantitative risk factor assessment scores, WC injury claims occurring to affected employees in the period two years prior to the intervention, and diagnosis codes and description narratives for those injuries. NVivo v.12 (QSR International; Victoria Australia), a computer software for qualitative data analysis, was also used to code narrative text in case study documentation reflecting on qualitative descriptions of the problematic process being addressed with the equipment intervention, description of risk factors, descriptions of effects on productivity, and descriptions of employee acceptance of the intervention and how this was assessed.

The effect of the intervention on productivity, was coded as an increase in productivity, decrease in productivity, productivity unchanged, or no description of an effect on productivity. This was based on identifying content in a cost-benefit analysis in the final report or in the written report narrative. An employer statement that qualitatively described a productivity increase or decrease was coded as such, even if no quantitative analysis was presented. Employee feedback/acceptance was classified as either *not describe*d or as *positive acceptance* by employees (either through an anecdotal comment by an employee(s) or through results of an employee survey). No descriptions of employee non-acceptance were encountered in any case studies. A single coder extracted (coded) the relevant information, with the exception of the workers' compensation claims. This coder was an individual with extensive experience in workplace safety intervention research and in conducting focus groups, including analysis with NVivo, for intervention research purposes. The workers' compensation claim descriptions were reviewed by two individuals for a joint consensus determination regarding the feasibility of the equipment intervention in preventing the injury precipitating the claim.

Over the program years changes were made to the grant application and how employers were instructed to document the WC injury claims to the affected employee population. In the earlier years, employers were instructed to list "…only those claims involving employees who are in the population." More detailed guidance was added in subsequent years asking for documentation of all injury claims to "…those employees directly affected by the proposed intervention." In the most recent years employers were instructed to document injury claims to the affected employee group "…that would have been affected by the intervention(s)." The most recent instructions address the more specific exposures which the intervention is intended to mitigate and the specific employees who had those exposures. The investigators reviewed all claim injury description narratives and determined the plausibility of the intervention technology in preventing each injury. This was believed to be in line with the most recent approach of identifying injuries that would have been affected by the intervention. Two levels were coded in this decision process for each injury description narrative based on the intervention equipment having either a plausible or an implausible mechanism of injury prevention. An example of an injury description narrative indicating an implausible mechanism of injury prevention reads, "Leaving breakroom stepped onto wet floor & slipped twisted & fell." This injury appears to have been documented in the application because it occurred to an employee in the worker group affected by the problematic process.

Injury claims were summarized according to a standardized *Injury Event/Exposure* code (2-digit), based on the Occupational Injury and Illness Classification System (OIICS) (Bureau of Labor Statistics, 2020). These event codes were auto-coded from injury narrative text using the methodology developed by the NIOSH, Center for Workers' Compensation Studies (Bertke et al, 2012; Bertke et al, 2016). Additionally, injury claims were assigned an *Injury Category*, which represents the category of injury based on the primary ICD-9 diagnosis code assigned by OHBWC in the claim acceptance (Meyers et al., 2018).

2.3 Analysis

Equipment purchase costs were inflation-adjusted to December, 2016 U.S. dollars using Economic Data from the Federal Reserve Bank of St. Louis, Producer Price Index by Industry: Industrial Machinery Manufacturing (Federal Reserve Bank of St. Louis, 2018). The equipment investment costs per affected employee were calculated for each case study by dividing inflation-adjusted equipment purchase cost by the number of affected employees documented by the employer.

Quantitative assessment of MSD risk-factor reduction was derived from the change in scores between assessments at the end of the two-year baseline period (when the intervention was implemented) and follow-up (1-year post implementation of the intervention). In many grants OHBWC consultants, and sometimes employer representatives, conducted a structured semi-quantitative assessment of upper-extremity, back, and lower-extremity MSD risk factors based on the 1995 OSHA Draft tool (Schneider, 1995; OHBWC, 2019). This instrument includes assessment of awkward postures, repetitive motion of the hand or wrist, contact stress, vibration exposure, and manual materials handling (MMH) loads/frequencies. Change scores (pre-intervention minus post-intervention) were converted to Z-scores and a percentile rank ordering according to the greater of the reductions in back or upper extremity musculoskeletal risk factors. For case studies that lacked a quantitative MSD risk factor assessment the authors indicated whether the case study final report contained a qualitative description of the intervention effect or no mention of an effect on risk factors.

3. RESULTS

Equipment Classification

A total of 112 grant awards were initially identified as meeting the search criteria and were manually reviewed. These represented approximately 4% of the total grants awarded through the SIG program during that time period. Of these, 76 had documentation (application and final report) deemed to be complete and sufficient to be included in the full review. None of the 2017 grant awards yet had final reports submitted at the time these data were received (in 2018), so only grants awarded through 2016 are included. Thirteen case studies were excluded after a more detailed review because the equipment being considered was a non-advanced (non-programmable) form of manufacturing automation. A common example of these exclusions was machining for a process that operated about a single axis to automate the application of shrink wrapping to palletized products. The final set included 63 employer case studies. Nearly all of these employers would be characterized as small manufacturing businesses, with only 3 of the 63 (4.8%) having greater than 250 employees. The remainder of the employer size distribution was: 7.9% - less than 10 employees, 47.6% - 10 to 50 employees, 23.8% - 50 to 100 employees, and 15.9% - 100 to 250 employees.

Based on the *a priori* interest in **Industrial Robots** (17 case studies) as interventions and the identification of many grants purchasing **CNC Machining** equipment (29 case studies, including routing, cutting, drilling, edge banding, etc.), the case studies were grouped into these two broader classifications in addition to a third classification of other programmable **Automated Systems** (17 case studies). The latter included equipment such as those for forming, material weighing and mixing, welding, pin marking, winding, bottling/labeling, among others. An example of one such system for material weighing and mixing was a Novatec Vacuum Positive Displacement Pump in combination with a WSB-140 weigh scale gravimetric blender (https://www.novatec.com/).

Forty-four percent (28 of 63) of these SIGs were awarded during the 2013–2016 years. A disproportionate number of grants in the later years of the period can be explained by an overall expansion of the program funding in 2013. Industrial robot interventions were awarded in somewhat greater numbers in the more recent 2013–2016 time period - 53% of the robot SIGs, 45% of CNC machines, and 35% of the Automated Systems being awarded during that period.

Appendix Table 1 lists all 63 case studies according to the technology category of the equipment, the industry, a brief description of the problematic (health/safety) work process, and the risk factors described by the employer as paraphrased from the application text. We have modified these descriptions for brevity while attempting to retain the actual text of the employer. Results are presented by an individual numeric reference key to each case study - the reader can refer to Appendix Table 1 for the case study description for each key. More detailed summaries of the industrial robot intervention case studies are documented as supplemental material accompanying this manuscript.

Equipment Investment Costs and Affected Employees

These 63 case studies accounted for capital purchases of nearly $12.27 million U.S. dollars (2016 adjusted), of which $2.43 million were subsidized through the OHBWC SIG program. Employers received the maximum grant program subsidy of $40,000 (nominal dollars) in 43 of the 63 case studies. Total equipment purchase costs (2016 US dollars) and costs per employee in the affected employee population are shown in Table 1. The table excludes three outlier case studies: (#4) of an automated palletizing system for packaging cheese by a Dairy Product Merchant Wholesaler, which represented a capital investment of $5.175 million (2016 USD), which is orders of magnitude higher than the typical equipment purchase through the SIG program. This automated palletizing system was described as affecting 60 employees, at an initial cost of $86,167 per affected employee. Case studies #15 and #44 were also excluded from affected employee summaries because they reported 155 and 216 affected employees, respectively, an order of magnitude above the averages. The highest expenditure per affected employee was $115,386 (case study #9, a CNC stone cutting system that was reported to affect exposures of only two employees. Excluding case study #4 the median total equipment investment per case study (employer contribution plus OHBWC subsidy, in 2016 USD) was $74,776 while the average was $114,385.

Figure 1 plots, for each case study, the grant equipment cost against the number of employees affected by the intervention. There is no apparent relationship between these two factors for automated systems or robotic equipment that would otherwise suggest greater investment in equipment when more employees might derive health safety benefit. This may be attributable to the variety of technologies, industries, and products produced in addition to the effect of the OHBWC program subsidy.

Initial Workers' Compensation Claim Injury Experiences

Across all case studies collectively there were 143 compensable claim injuries among the affected employee work groups in the two-year baseline periods prior to implementing the interventions. The baseline period injury claims were concentrated in 31 of the 63 grants. Figure 2a shows counts by injury category, and Figure 2b shows counts by injury event/exposure. The most common injury category was *open wounds* (n=26), followed by *upper extremity sprains* (n = 20), *back sprains* (n =17), and *enthesopathy* (t*endon or ligament inflammation or disorder)* (n = 17). Injury event/exposures were most frequently due to *overexertion involving outside sources* (n = 48) and *struck by object or equipment* (n = 28), which accounted for the majority of the injury event/exposures. Through the investigators' review of the injury claim description narratives it was determined that 27.3% (39 of 143) of the injury claims would not have been plausibly preventable with the intervention equipment subsequently acquired.

Risk Factor Reduction

There were 33 case studies with comparable pre- and post- MSD assessments conducted so that a risk factor reduction score could be calculated. These are shown in Figure 3 with MSD risk factor reduction scores ranked in descending order by converted percentile for the higher of the upper extremity and back/leg MSD risk factors. Choosing a criterion of less than $9,285 in cost per affected employee (equal to the geometric mean of all case studies) identifies five case studies with a quantitative risk factor reduction (upper extremity or back/legs) in the top quartile and with increased productivity reported (see Appendix Table 1). These are CNC Stone Cutting systems (case study #1), CNC/Vertical Machining for light highway construction equipment manufacturing (#6), Automated system for bottling (#7), CNC/Routing in plastics products manufacturing (#8), and a CNC/Cutting system for vinyl/carpet (#10). Of these, only case studies #6 and #8 were associated with any compensable injuries in the two-year baseline period prior to intervention implementation (Appendix Table 1). The “outlier” case study, #4, described above, was associated with 23 total claim injuries in the baseline period and one of the highest reductions in MSD risk factor scores, but the equipment cost per affected employee was high and the case study reported that the equipment intervention had no effect on productivity.

Case studies in the second quartile of risk factor reduction with cost per affected employee less than $9,285 included seven with reported productivity increases: CNC plasma cutting of sheet metal in HVAC system fabrication (case study # 12); CNC Die press cutting of vinyl in disposable medical device manufacturing (#14); Robot for pick and place vertical packing (#15); Automated blending/weighing system for blending raw materials in plastic extrusion processes (#16); Automated bottling/labelling system in a brewery (#17); Automated channel bending system (#18); Robot for pick and place in a microelectronics application (#19); CNC Routing System used in sporting and athletics goods manufacturing (#21); and a CNC rubber cutting system for the fabrication of hoses, power belts, and gaskets (#23). Among these, only case studies #14 and #15 were associated with baseline period claim injuries, of which there were 10 each, with 18 of the 20 due to overexertion or repetitive motions.

These can be contrasted with case study #29, a CNC machine for stone cutting granite countertops, and #33 a robot used for eliminating manual holding of workpieces in a brush plating process, both in the bottom quartile of those reporting MSD risk factor reduction and with cost per affected employee of $11,543 and $28,354, respectively. Though MSD risk factors were reduced to a lesser degree for case studies #29 and #33, these case study reports describe elimination of silica dust and reduction of noise exposure (#29) and “limiting their exposure to a chemical environment” (#33). No baseline period injuries were reported in these case studies.

Of the case studies of industrial robots, 6 of 17 (35.3%) reported reduction in MSD risk factors with complete quantitative assessments and 9 of 17 (52.9%) with only qualitative descriptions of improvement in risk factors, which included:

> “Exposure to repetitive motion injuries, relating to this specific work, has been eliminated.”
>
> (case study #44)

> “The intervention eliminated soft tissue type risk factors and occupational hazards of hot metal burns. … This intervention eliminates the repetitive motion by the employee since the robot would now do the repetitive motion. Due to the intervention, we have had no burns due to the operation of the

> die cast machine, carpal tunnel from repetitive motion, rotator cuff sprains, strains or tears, and cuts from sharp castings."
>
> (case study #45)

> "The robot performs all cutting and placing of the parts onto a conveyor belt. This has resulted in zero exposure to our associates. The addition of a robot has allowed our associates to inspect the finished product more thoroughly while removing the most hazardous portion of our process."
>
> (case study #49)

> "… as a result of their financial constraints the project was put on hold. …Despite these setbacks we still recognized the value in implementing a robot transfer for piercing heads. The repetitive nature of the process, ergo assessment for the operator, as well as the production savings where obvious."*.
>
> (case study #50)

(*ergo assessments were not included in final report)

> "By establishing jigs on the turn tables we have reduced potential injuries in the areas of lumbar, knee, shoulder, upper arm, rotator cuff, radius/ulna and wrist. There is less physical stress on the body compared to our normal daily processes. We have reduced potential injuries that pertain to daily use of nail guns and reduced injuries in the areas of finger, hand, wrist, shoulder/upper arm, and rotator cuff."
>
> (case study #55)

Intervention(s) improved safety by:

> "Reducing repetitiveness to body parts and prolonged sitting, not limited to the following: back, neck, arms, shoulders, fingers, legs, and wrists. Carpel tunnel injuries, Shoulder sprains or strains, Lower back muscle strain, Epicondylitis, Varicose veins".
>
> (case study #56)

> "BEFORE - Operators walked into the machine to manually insert fill necks into mold cavity with machine in semi-automatic mode - Safety Risk. AFTER - Operators do not enter machine- safety risk minimized."
>
> (case study #57)

> "(The) intervention prevents potential incidents occurring with the repetition of the debur process".
>
> (case study #60)

> "(The) Collaborative Robotic Arm has eliminated the thousands of hand motions from the operator during the work shift. This intervention has greatly reduced the risk of injury or developing illnesses associated with a repetitive work environment."

(case study #61)

The broader classifications of equipment type exhibited different trends when comparing the impact on risk factors to the upper extremities versus those for the back/legs (see Figure 3). CNC equipment generally had greater impact on reducing upper extremity risk factors rather than back and leg musculoskeletal risk factors. This is somewhat intuitive as these processes tend to substitute for handheld tooling or processes rather than for heavier manual handling. Exceptions to this were case study #5, which incorporated a crane/hoist to assist the operator getting plates on and off the CNC vertical machining center and eliminated the hand lifting of plates; #14, which included powered pinch rollers to feed vinyl sheet stock into the machine and eliminated manual pulling to advance the material; #21, which included a powered lift table in addition to the CNC router; and #24, which was a new, improved CNC routing system with multiple rather than a single head that, according to the employer, “reduce(s) some of the MMH they [employees] now perform in the more complex pieces.”

The automated systems tended to have greater impact on the back/legs by eliminating manual handling and MSD risk factors of the weight handled and frequency/postures associated with the handling. Examples include handling 5 gallon/43-pound pails in case study #2, 30-pound cases of cheese, and 80-pound pallets in case study #4, and high cumulative handling of loads in a bottling process in case study #7. One exception was case study #13, a programmable computer-based control system for knot brush assembly, that included a smaller machine base to reduce upper limb reach distances (and machine guarding/light curtain in the load/unload area to protect from traumatic injury to the hand), and for which back/legs risk factors were minimal before the intervention. A second exception was case study #30, in which an automated marking machine/etching system eliminated the use of manual hammers to stamp serial numbers into pipe fittings, and for which back/legs risk factors were also minimal before the intervention. The industrial robot interventions did not exhibit a trend towards greater benefit on upper extremity or back/legs risk factor reduction. Overall, the robot interventions appear to have reduced MSD risk factors to a lesser degree than the other types of interventions.

Employee Acceptance of Interventions

Thirty (30) case studies described employee acceptance in the final report. In 29 case studies this was based on limited anecdotal employee feedback, while one (1) case study contained results from a structured survey administered by the employer. The industrial robot case studies reported acceptance in 53% of case studies (9 of the 17), automated systems in 47% of case studies, and CNC machines in 45% of case studies. Examples of text indicative of positive employee acceptance include:

- “We interviewed one of the men… to ask him what he thought about the intervention. His face lit up with a smile as he said in gratitude, It took the place of having to lift the heads by hand. You can only do that for a couple of hours before you’re spent. He also added that, it had to have helped production because it took the place of two guys so they could do other stuff. I asked … if he thought the project was a success. He said he thought it was a success and that it ran smooth once it was up and running."

- "Employees have liked being out of the welding fumes and are less fatigued at the end of the day. Employees also like that they do not need to wear air supplied welding helmets."
- "Employees provided positive feedback on the efficiency of the cell as well as not having to enter the machine while running production."
- "Feedback from affected employees has been positive. The work in this area is less taxing to the operator over an 8 hour shift."
- "Feedback has been very positive. Eliminating the 408 repetitive movements during the 10 hour work shift has made for a less taxing work environment and greatly reduced the risk of injury or developing illnesses associated with a repetitive work environment."
- "The employees enjoy using this new piece of equipment. They don't have to strain themselves or do the tedious repetitive task of rubbing anymore."
- "They are much happier not deburring every day and getting the aluminum dust on their skin (we had employees with reactions). They also like not having to load the laser as some of the employees (not all) were concerned if they ever looked into the laser and it affected their eyesight."

The single case study (#48) with a structured employer-administered survey contained the responses of two employees (of three total affected employees for the case study). Both employees indicated "yes" to questions about whether they used the insertion machine; whether it was helpful; whether the machine increased the speed of jobs ordered; was accurate; and made it easier on their back, shoulders, and eyes. Both indicated having received adequate training on the machine and both reported a highly positive experience with the equipment.

Strength of Case Studies

Intervention case studies may be considered stronger and have more impact if they exhibit the following attributes: reduction in risk factors demonstrated with quantitative assessments, lower cost of the equipment relative to the number of employees affected by the work process, positive effects on productivity, and employee acceptance of the intervention. An injury claim(s) history may indicate a greater case for the health/safety burden of the pre-intervention work process. Only two case studies in this review were consistent with all of these attributes: case study #14, a CNC Machine for die press cutting used in the Electromedical and Electrotherapeutic Apparatus Manufacturing, and case study #31, a robot for welding used in the leather goods and allied products manufacturing. Dropping the requirement for pre-intervention injuries includes nine additional case studies meeting the criteria. There were six CNC machining equipment interventions:

- #1 – cutting stone in cut stone and stone products manufacturing,
- #10 – carpet and vinyl cutting in floor covering manufacturing,
- #12 – plasma cutting in sheet metal work manufacturing,
- #21 – routing in sporting and athletic goods manufacturing,
- #23 – rubber cutting in rubber products manufacturing for mechanical use, and
- #24 – routing in custom architectural woodwork and millwork manufacturing.

There were three other programmable automated systems:

- #7 – automated system for bottle filling in a winery,
- #17 – automated system for bottle labelling in a brewery; and
- #16 – automated system for loading, weighing, mixing and delivering plastic pellets to an extruder in plastics manufacturing.

Among the case studies of industrial robots, the stronger case studies include the following.

- In case study #15 a robotic/pick & place packer (Vertical packer) was implemented in the Snack Food Manufacturing industry for manual picking and placing of bags in boxes. Because of the speed of the equipment and the number of repetitions involved to place the bag into the box the employer had experienced several upper extremity injuries related to hands, wrists, forearms, elbows, upper arms, and shoulders with WC claims for Carpal Tunnel Syndrome (1), Diseases of the Nervous System and Sense Organs (1), Soft tissue/ Enthesopathy (3), Sprains - upper extremity (3), and Sprains-Back (2). Risk factors for musculoskeletal disorders/injuries were eliminated by substituting the robotic pick and place vertical packer for human labor. The quantitative score for upper extremity MSD risk factors was reduced from 14 to 4 and those for the back/legs reduced from 10 to 2.
- In case study #19 the employer purchased a high-speed programmable robotic pick-and-place system in a micro-electronics application for assembly of membrane switch/dome assemblies. No workers' compensation claim injuries were reported among this affected employee group in the baseline period. However, risk factors included use of poorly designed hand tools, pinching and gripping causing stress on the arms, hands, and wrists, material handling of small parts, being struck by moving parts, repeated motion, and poor workspace layout. The exposures to risk factors for upper extremity musculoskeletal injuries/disorders during dome placement were nearly eliminated by substituting robotic pick-and-place placement for human labor. The quantitative score for upper extremity MSD risk factors was reduced from 14 to 2.
- In case study #20 an employer in the Precision Turned Product Manufacturing Industry acquired an industrial robot for a collaborative application to replace human labor for repetitive metal cylinder deburring and sanding tasks. Operators had to use hand, wrist, elbow, and shoulder movements repetitively over

the 10-hour work shift at a frequency of approximately 68 parts per hour and 6 movements per part with an average part weight of 10 pounds. Employees' exposure to risk factors for musculoskeletal injuries/disorders and cuts/lacerations were eliminated by substituting the collaborative robot arm for human labor. The quantitative score for upper extremity MSD risk factors was reduced from 18 to 6. Productivity was stated to be unchanged.

- In case study #25 an employer in the Plastics Product Manufacturing Industry acquired a six-axis modular robot mounted on a rotating stand with a cutting system. The robot was programmed to remove the plastic molded parts from the mold cavity, move away from the molding machine, cut the gate flush on the individual molded parts and place the parts on a conveyor. No claims or injuries were reported during the 2-year baseline period. However, turnover in this department was 20%, and hand intensive work and repetitive motion were identified as risk factors that could result in hand, wrist, finger, arm and shoulder injuries. Employee exposures to musculoskeletal risk factors were nearly eliminated by substituting the robot-held cutter for human labor to cut the molded par gate. The quantitative score for upper extremity MSD risk factors was reduced from 18 to 8, and risk factors for the back/legs reduced from 4 to 1. Productivity was stated to be unchanged.

4. DISCUSSION

Risk Factor Reduction

The results of this review emphasized the ergonomic/musculoskeletal risk factor reduction (before and after the intervention) as assessed with the OHBWC semi-quantitative instrument. Safety hazards associated with traumatic injury outcomes were often described in report narratives but were infrequently reported pre- and post-intervention with complete safety hazard assessments with the OHBWC instrument. Only seven case studies (#1, #6, #20, #21, #26, #52, #59) had complete pre- and post-intervention assessments of safety hazards, with all seven showing reductions in the overall hazard scores. One of those seven, case study #20 was an industrial robot intervention, which the employer stated eliminated repetitive tasks for the operator and therefore eliminated risk for developing repetitive use injuries. The safety assessment score reduction from 69 to 8 in that case study described initial specific hazards of *grabs part to be sanded, holds part to chamfer sander, sands part with multiple motions*, and *inspects part and re-sands if needed* for which most of the associated hazards were eliminated.

Ten case study grant applications described new risks introduced by the proposed automation equipment. Seven of these mentioned the need for additional machine guarding (#23, a CNC system; #43, an automated system for palletizing; and five industrial robot interventions: #44, #46, #47, #55, #56); one mentioned increased noise exposure with the new equipment that was "not anticipated to rise above threshold levels" (#30); one mentioned "potential buildup of static electricity and subsequent discharge" (#16); and one mentioned that the CNC router would result in increased manual use of a utility knife (#21). None of these case study reports described injuries or health/safety outcomes as resulting from these potential risks in the one-year final report. It may be seen as a positive that these employers gave consideration to new hazards that might be introduced with the intervention equipment. In a few cases this consideration referenced relevant consensus standards for risk assessment for the integration of an industrial robot (ANSI, 2012).

While the present study does not allow conclusions to be drawn about injury outcomes (WC claims), a reduction in risk factors for musculoskeletal disorders was shown consistently across all the forms of equipment interventions where manual aspects of tasks were allocated to the automation machinery. This is consistent with a review of case studies by Goggins et al (2008) showing that individual control measures with semi-automation of processes to eliminate key exposures were greater in effectiveness, as established by reduction in WMSD incidence rates, lost work time, and claim costs, than forms of controls that reduced level or duration of exposure or that relied on worker behavior. Manufacturing automation interventions included in the present review, by definition, eliminated certain task exposures and risk factors by the allocation of function to a machine. Similarly, a National Council on Compensation Insurance report (Davis and Crotts, 2010) identified advances in automation, technology, and production (specifically identifying increased use of robots) as a factor contributing to the decreased WC injury claim frequency at that time period.

Introduction of automation has many effects on operator performance, and these should be considered by designers, supervisors, managers, and regulators (Parasuraman and Riley, 1997). An extensive body of human factors literature addresses human error and system performance that result from automation and human capabilities in information acquisition, processing, and decision making (Parasuraman et al., 2000; Lee and Seppelt, 2012). The present case studies of manufacturing industry applications are examples of automation equipment substituted for mostly physical, rather than information processing or decision support, functions. These were tasks that would otherwise require input of mechanical forces or repetitive physical exertion by the human operator. The allocation of these functions to the automation was deemed to be an appropriate intervention approach, not for the goal of reducing human error, but to prevent operator injury.

Employee Acceptance of Interventions

Potential adverse effects of robots and automation on employee attitudes and acceptance have been described as resulting from eliminating or diminishing the role of human workers in production processes. These include macro-ergonomic, psycho-social, and/or economic factors. Some studies suggest the adoption of information and communication technologies (Michaels et al, 2010) and robotics (Acemoglu & Restrepo, 2017) has adversely impacted earnings and employment opportunities, respectively, for medium- and low-skilled workers and have expressed concern these effects will increase over time. Other research associates the adoption of automation and, in particular, robotics with workers' concerns about fear of job loss or insecurity/redundancy, reduced future earnings (Wischniewski et al, 2022; Gutelius and Theodore, 2019; Patel et al, 2018), and job deskilling and/or loss of meaningful work (Smids et al, 2020) - psycho-social stressors that can result in adverse health outcomes. Conversely, some studies have suggested that concerns regarding worker displacement by robots are exaggerated, and they portray robotics favorably in the context of increasing total factor productivity, increasing average wages, and reducing output prices (International Federation of Robotics, 2017; Graetz and Michaels, 2018). These case study final reports were prepared from the employer perspective and descriptions of non-acceptance of the intervention by way of negative feedback from employees was rarely found. This may reflect some degree of positivity bias in which employers, wanting to support the grant award process, were reluctant to describe negative aspects of the experience from the perspective of employees.

In a number of grant applications employers anticipated that fewer employees would be needed in a work process after implementing the automation equipment. Employer applications tended to describe that these employees would be reassigned to another task or process within the firm. The following grant application narrative is an example of such a description.

> "The unskilled labor causes many more man hours to be spent at the machines, increasing the potential for near misses or claims. The reason for the intervention is to try to eliminate this problem altogether by the use of a CNC Vertical Machining Center (VMC). However, this will not result in any eliminated positions. Instead, these employees will be able to work in different departments, resulting in increased productiveness in other departments as well."
>
> (Case Study #6)

Final reports rarely expanded on how labor hours saved due to the automation resulted in reassignment of the worker elsewhere within the business. In nearly all cases increases in productivity were achieved by eliminating or reducing the employees needed to achieve an equivalent output due to the automation. It is worth noting that the OHBWC SIG program has a policy statement that receiving a grant for equipment purchases should not result in employment loss for any employees.

The OHBWC SIG program prioritizes worker safety and health as the motivation for the purchase and use of equipment interventions. However, anticipated benefits on productivity from these automation technologies also appear to have been a significant incentive to employers in implementing the equipment. Additionally, the SIG program recognizes the importance of productivity effects due to the intervention, asking the employer to address this in both the application and final report. Seventy-six percent of employers described benefits of the equipment on productivity, although a cost/benefit analysis with payback period requires more complete cost information than these case study reports typically provided. More detailed costs for engineering planning and design, employee training, recurring maintenance, and other equipment lifecycle costs (Mossink, 2002) were reported infrequently and inconsistently, making it difficult to interpret cost/benefit and return on investment in aggregate.

These case studies suggest that there are opportunities for manufacturing sector employers, at least smaller U.S. employers, to implement automation to reduce identified workplace hazards. Numerous examples were observed of insurer-incentivized equipment interventions to reduce identified risk factors in diverse manufacturing processes by automating aspects of the work. Many, but not all, of the interventions were noted to improve productivity. Smaller enterprises may have a greater reliance on economic justification for undertaking such capital investments (Cagno et al, 2013). Thus, a need may exist to provide smaller employers in particular with resources for determining monetary costs, benefits, and calculating return on investment of equipment purchases to mitigate workplace hazards.

Study Limitations

There are several limitations of the data to consider when interpreting the findings. The sample size (number of case studies and employees in the affected processes) is small, and statistical power to examine effects of the interventions on injury outcomes (WC claims) is lacking. A participation or self-selection bias may exist because SIG program participant employers tend to have slightly higher injury claims rates overall than other comparable employers in their industry and size classification (Wurzelbacher et al, 2014). This potential bias on evaluating health outcomes should not be influential on reduction or elimination of exposures (risk factors), which was the focus of the review. Furthermore, changes over the years in the program eligibility requirement with regard to having one or more injury claims in the baseline period *attributable to the specific task* could have differentially affected the findings over the time period. SIG program participant employers in manufacturing businesses may not be representative of the Manufacturing Sector on the whole. Participating employers in the SIG program tend to be smaller-sized employers. Smaller employers tend to have fewer in-house resources and capabilities for assessment and control of employee exposures to risk factors, and they may receive less regulatory oversight through inspection/enforcement activities (Leviton and Sheehy, 1996). Another limitation is the potential for positive reporting bias. Approximately 20% of grant recipient experiences were not included because of missing or incomplete final reporting.

In several cases a pre-intervention MSD risk factor assessment was conducted but there was no documentation of a corresponding post-intervention assessment. In those cases it is possible a follow-up assessment was deemed to be unnecessary because the automation simply eliminated the specific problematic task with MSD risk factors. However, this was difficult to discern, and experience with these data suggests that some case studies were submitted without follow-up assessments even when residual musculoskeletal risk factors are known to exist. Additionally, while the MSD instrument is a semi-quantitative means of assessing known risk factors, the predictive value of the resulting scores for either the upper extremity or back and legs have not been established. There are no risk threshold values using this specific assessment tool that have been established as being protective for musculoskeletal disorders.

5. CONCLUSION

Risk factors were, in almost all case studies reviewed, described as having been reduced by industrial robots and programmable manufacturing automation equipment implemented as health/safety interventions by small Ohio businesses. While only half of the case studies reported quantitative assessments pre- and post-intervention, CNC machining interventions tended to have more benefit in reducing upper limb MSD risk factors (wrist, forearm, shoulder awkward postures, forceful gripping, contact stresses, and vibration). Industrial robots reduced MSD risk factors overall, but a primary benefit towards upper limb versus the back/leg risk factors was not clear. Other types of automated systems seemed to have more benefit on reducing back and leg risk factors by means of reduced trunk bending, kneeling/squatting, and pushing, pulling, or lifting loads and awkward postures. While 76% of case studies described increases in productivity in the final report narratives, quantifying these effects was not possible with the information in the final reports. This review of case studies suggests opportunities for robots and programmable manufacturing automation to reduce workplace risk factors while improving productivity. However, the financial incentive provided by the OHBWC grant program and incomplete cost-benefit reporting limit the ability to interpret how a return on investment would be experienced by these, or other, employers.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Appendix Table 1

case study (key)	technology classification/specific intervention	year	cost (2016 USD)	Industry	Problematic Process	Employer Description of Risk Factors #	Back/Legs risk - %tile reduction	Upper Extremity risk - %tile reduction	effect on productivity	Employee acceptance	injuries preventable by the intervention (category)	injuries preventable by the intervention (event/exposure)
1	CNC/Cutting (Stone)	2014	321,343	Cut Stone and Stone Product Manufacturing	Manual edge miter tasks creating slurry on stone surface	Hand mitering of edges for cut stone requires excessive forceful exertions and deficient back and shoulder postures. High forceful exertions (lifting, carrying, pushing and pulling).	98.5	99.7	↑	Acceptance	none	none
2	Automated/Filling, weighing	2008	130,865	Polish and Other Sanitation Good Manufacturing	Manually filling Buckets with product using fill hoses and then manually lifting, carrying and palletizing filled buckets	Repetitive motions every few seconds with a grip of more than a 10 pound load. Awkward Postures include unsupported shoulder with arm or elbow above mid-torso height. Hard/Sharp objects press into skin. Severe forward bending of the torso more than 45°. Twisting Torso. The pails being handled weigh approx. 45 lbs.	98.5	50.7	?	Acceptance	Burn (1) Contact Dermatitis and other eczema (1) Sprains - other (1) Sprains - upper extremity (3) Sprains-Back (2)	Caught in or compressed by equipment or objects (1) Exposure to other harmful substances (2) Overexertion involving outside sources (5)
3	CNC/Routing	2014	33,709	Plastic Products Manufacturing	Operating drill press and hand-held pneumatic rotary tool	Repetitive stress on the wrist, forearm, and shoulders of the drill press operator. deburring operator. Wrist: Gripping the tools with force, turning and rotating wrists. Forearm: Rotating motion is repetitive causing stress on forearm. Non-neutral posture of the shoulder:	30.2	97.7	↔	Acceptance	none	none
4	Automated/Palletizing	2010	5,174,800	Cheese Manufacturing	Manual handling of pallets, stacking boxes on pallets and shrink boxes on pallets.	Constant repetitive motion to manually stack 6–30 lb product onto a pallet from floor to waist requiring bending, flexing and overextending of the back. Fully stacked pallets can weigh anywhere from 468lbs to 2000lbs and are manually moved with a hand truck.	97.6	57.8	↔	Not Described	Contusion (8) Crushing Injury (1) Fracture - lower extremity (1) Open Wounds (3) Sprains - lower extremity (3) Sprains - other (1) Sprains - upper extremity (1) Sprains-Back (4) Superficial injury (1)	Falls on same level (6) Other exertions or bodily reactions (2) Overexertion involving outside sources (5) Slip or trip without fall (1) Struck against object or equipment (5) Struck by object or equipment (4)
5	CNC/Vertical Machining	2011	152,688	Railroad Rolling Stock Manufacturing	Hand operations such as putting chamfers on parts	Back injury from lifting plate from cart to band saw machine or burning table. Strains, sprains, broken bones, abrasions or contusions from falling parts; back injury from restacking finished parts on carts.	96.4	36.5	↑	Not Described	none	none
6	CNC/Vertical Machining	2010	66,075	Construction Machinery Manufacturing	Manual repetitive operation of a drill press quill	Exposure to chemical hazards while drilling. Exposure to continuous heavy loads in the 75 – 90 pound range that are of awkward shape. Due to the multiple drilling operations, the parts must be handled several times. Repetitive arm, hand and shoulder motion due to the nature of pulling the hand lever up and down.	76.8	94.9	↑	Not Described	Open Wounds (1)	Struck against object or equipment (1)
7	Automated/Bottling	2013	60,500	Breweries	Manual bottling sanitizing, filling & capping using bottle filler and bottle capper.	No narrative description of risk factors.	92.6	24.1	↑	Acceptance	none	none
8	CNC/Routing	2010	84,882	Plastic Products Manufacturing	Hand finishing and trimming including counterboring, routing, drilling, cutting and sanding	Hand trimming of fiberglass reinforced composites requires the operators to constantly move, flip and rotate small to very large parts. Awkward, poor ergonomic postures, vibration, extended reaches, and heavy forces needed to operate the trimming tools. Vibration—the body must absorb the vibration of the tool as it cuts. Extended reaches due to bulkiness of many products. Heavy forces—pressure must be added to allow the tools to cut, trim, and drill.	19.0	89.9	↑	Not Described	Fracture - upper extremity (1) Soft tissue/Enthesopathy (3)	Overexertion involving outside sources (3) Struck by object or equipment (1)
9	CNC/Cutting (Stone)	2013	230,772	Cut Stone and Stone Product Manufacturing	Use of pneumatic and electric hand-held powered tools to edge detail	Stone is moved on average 4 to 6 times during the fabrication process and staging for installation. The major injury concerns for these tasks are the weight handled [of the router/edger itself, excessive repetitive motions, forceful exertions, and awkward body postures of the back, neck, shoulder, arms and hands. Pressure produced by coming into contact with sharp edges and tools.	76.8	89.9	↑	Acceptance	none	none
10	CNC/Cutting (Vinyl,carpet)	2004	27,909	Floor Covering Manufacturing	Cutting carpet or vinyl with a knife	Manually cutting vinyl and carpet places employees in uncomfortable positions (working on knees), but also exposes them to cutting injuries.	50.6	82.0	↑	Acceptance	none	none
11	CNC/Cutting (Metal)	2014	30,538	Fabricated Metal Product Manufacturing	Operating a horizontal band saw	Forceful exertions of the upper extremities to lift 48–60 lbs saw handle. The current saw requires manual clamping and un-clamping of the stock by turning a tightening wheel and manually moving the material forward in the saw. Twisting, turning and bending repetitively while using the saw. Awkward postures of the upper extremities and lower extremities.	36.7	76.9	↑	Acceptance	none	none
12	CNC/Plasma cutting	2013	51,355	Sheet Metal Work Manufacturing	Manual cutting, and notching using non-powered hand snips and tools	Exposure to repetitive usage of hand tools — static standing and bending over — awkward postures to the wrists and elbows. Repetition of using manually powered hand tools to cut, notch, trim up to 12 cuts on a piece of sheet metal.	50.6	71.1	↑	Acceptance	none	none
13	Automated/Knot brush assembly	2003	84,299	Broom, Brush, and Mop Manufacturing	Knot wheel machine for brush manufacturing	Leaning and reaching across the machine and above shoulder level. Repetition of pulling the last knot away from the point of operation. Risk involving gloved hand where pinch points and rotating machine parts are present.	14.6	64.7	↑	Acceptance	Fracture - upper extremity (1)	Caught in or compressed by equipment or objects (1)
14	CNC/Die press cutting	2003	52,835	Electromedical and Electrotherapeutic Apparatus Manufacturing	Die cutting machine and manual pull of vinyl from roll across dies	Pulling on five layers of vinyl utilizing a pinch grip. Each roll of vinyl stock weighs up to 100 lbs. and is fed from a free wheeling pin.Repetitive awkward postures while die cutting continuous sheet (roll) vinyl. Extended reaching (using force), Upper torso twisting, Forceful gripping (pinch and power), Reaching above the shoulders. Awkward posture wrist & elbow.	64.6	24.1	↑	Acceptance	Carpal Tunnel Syndrome (1) Disc Disorders (1) Soft tissue/Enthesopathy (2) Sprains - lower extremity (1) Sprains - Neck (2) Sprains - upper extremity (3)	Overexertion involving outside sources (6) Repetitive motions involving microtasks (3) Slip or trip without fall (1)

case study (key)	technology classification/specific intervention	year	cost (2016 USD)	Industry	Problematic Process	Employer Description of Risk Factors #	Back/Legs risk - %tile reduction	Upper Extremity risk - %tile reduction	effect on productivity	Employee acceptance	injuries preventable by the intervention (category)	injuries preventable by the intervention (event/exposure)
15	Robot/Pick & place (Vertical packer)	2005	640,948	Other Snack Food Manufacturing	Manual picking and placing bags in boxes	Number of repetitions and speed involved to place the bag into the box. We experience injuries related to hands, wrists, forearms, elbows, upper arms, and shoulders. Most of them are sprain/strain type injuries, but others escalate to CTS and tendonitis involving time away from work or surgery.	64.6	43.5	↑	Not Described	Carpal Tunnel Syndrome (1) Diseases of the Nervous System and Sense Organs (1) Soft tissue/Enthesopathy (3) Sprains - upper extremity (3) Sprains-Back (2)	Falls on same level (1) Other exertions or bodily reactions (1) Overexertion involving outside sources (5) Repetitive motions involving microtasks (3)
16	Automated/ Blending,weighing	2013	60,129	Plastics Product Manufacturing	Manual transfer using buckets and shovel	Repetitive reaching and lifting in forward bending posture. Use of a shovel to loosen up the resin. Bending over the edge of the gaylords and reaching down into the gaylords that are as much as 46" deep and lifting buckets weighing 20 to 30 pounds out of the gaylords.	64.6	24.1	↑	Acceptance	none	none
17	Automated/ Bottling,labelling	2016	75,194	Breweries	Manually placing labels on bottles and stacking on pallet	Manual material handling (lifting, lowering, carrying, bending, twisting), repetition per month of over 1000, double/triple handling, handling weight. Exposure to awkward body posture of the lower extremities, upper extremities, and trunk. Exposure to hand, wrist, arm, and shoulder repetition. Exposing employees to possible carpal tunnel syndrome.	64.6	30.0	↑	Acceptance	none	none
18	Automated/Channel bending	2010	85,346	Sign Manufacturing	Manual metal bending tools	Bending and notching, exertion of high amounts of force while often assuming awkward postures to form the letters. The injury risk is increased as the size, thickness, and hardness of the alloy increases.	57.7	57.8	↑	Not Described	none	none
19	Robot/Pick & place (Micro electronics)	2011	77,672	Photographic Film, Paper, Plate, and Chemical Manufacturing	Manual methods for membrane switch assembling	Using hand tools and techniques to pinch and grip with the hands and wrists. Physical hazards include material handling of small parts, being struck by moving parts, poor tool design, repeated motion, and poor workspace layout.	14.6	57.8	↑	Not Described	none	none
20	Robot/Universal Robot UR10 (collaborative robot application)	2015	51,429	Precision Turned Product Manufacturing	Rotating chamfer and sander tool (not fully described)	Operators use hand, wrist, elbow and shoulder movements repetitively over the 10 hour work shift at a frequency of approximately 68 parts per hour. The operator is required to make approximately 6 movements per part. The average part weight is up to 10 pounds. Required grip pressure to grasp parts is approximately 2 psi. Hand intensive work with Lifting, Repetitive motion, and Vibration exposure.	30.2	57.8	↔	Acceptance	none	none
21	CNC/Routing	2014	54,229	Sporting and Athletic Goods Manufacturing	Hand-held router	Above average size and weight and long or awkwardly shaped products (20–90 lbs) preclude use of machines to efficiently move. Cutting, drilling, routing, and assembly are all performed at one station. Repetitive hand vibration and force exertion.	57.7	18.8	↑	Acceptance	none	none
22	CNC/Routing	2013	109,834	Architectural Metal Products Manufacturing	Hand cutting sheet metal wall panels	Employees carry sheets from one station to the next. The risk of injury increases due to handling multiple times carrying, kneeling, bending, and pushing.	30.2	50.7	?	Not Described	Open Wounds (1)	Struck by object or equipment (1)
23	CNC/Cutting (Rubber)	2013	151,316	Rubber Product Manufacturing for Mechanical Use	Box cutters and knives to manually cut different rubber products	The major injury concerns for this job tasks, are the weight of the various materials carried, lifted and transporting to the cutting tables. Also, there are forceful exertions and awkward body postures of the back. neck, shoulder, arms, wrist and hands while hand cutting the various rubber types.	50.6	50.7	↑	Acceptance	none	none
24	CNC/Routing	2014	63,059	Custom Architectural Woodwork and Millwork Manufacturing	CNC machine with one operating head and hand-held power and non-power tools	Repetitive motion injuries and ergonomic related injuries from lifting and/or pushing or pulling of lumber or material.	43.5	24.1	↑	Acceptance	none	none
25	Robot/Fanuc ArcMate 100iB	2015	53,471	Plastics Product Manufacturing	Manually trimming plastic molded gate	Hand intensive work with repetitive motion.	30.2	43.5	↔	Acceptance	none	none
26	CNC/Cutting (Fabric)	2010	97,241	Upholstered Household Furniture Manufacturing	Scissors, electric cutter and cutting table	Awkward wrist postures when cutting fabric. Working with hands above shoulder height to remove fabric from racks. Awkward postures of the back and shoulder when reaching to position and cut fabric on the cutting table.	36.7	36.5	↑	Not Described	none	none
27	CNC/Vertical Machining	2004	81,788	Hand Tool Manufacturing	Manual drill press	Repetitive motion of the hands and wrist. Pinch grasp in movement of part from the tray to the point of operation. Awkward position of head and neck when completing a 2 part drill.	7.9	36.5	↑	Acceptance	Carpal Tunnel Syndrome (1) Soft tissue/Enthesopathy (1)	Overexertion involving outside sources (1) Repetitive motions involving microtasks (1)
28	CNC/Cutting (Polymer sheets)	2012	77,214	Commercial Screen Printing	Various equipment, including band saw, router, drill press, table saw, miter saw, table saw, rip saws, and utility knives.	Lifting, manipulating and pushing materials (weighing up to 83 lbs) against a saw gate through a moving saw blade. Exposure in the cutting area averaged about 900 work hours per year over the past 2 years. Strains and sprains are also possible due to the material handling and manipulation of both the material and the tools. Awkward postures and extended reaches are the norm.	19.0	30.0	↑	Not Described	Open Wounds (1)	Struck against object or equipment (1)
29	CNC/Cutting (Stone)	2013	138,512	Cut Stone and Stone Product Manufacturing	Stone saw and hand-held pneumatic stone polishing tools	Push and pull issues on the saw cutting table along with lifting and moving pieces to the rolling cart. Employees maintaining static work and hand/arm/elbow -postures during repetitive hand tool cutting/buffing/deburring granite marble counter tops.	24.2	24.1	↑	Not Described	none	none
30	Automated/ Marking,etching machine	2011	31,967	Fabricated Pipe and Pipe Fitting Manufacturing	Embed serial numbers on to metal pipe using hammer or Hilti gun	Large hammer forces to embed the serial numbers into the metal. The hammer weighs 2 pounds. Jarring of the shoulder occurs on impact. Sustained postures must be maintained by the left hand to hold the number stamp in place. Grip and hold the stamp in place for the 3–5 minutes of stamping. Awkward shoulder and elbow postures are needed to hold the 11 lb gun tool in the proper position.	14.6	24.1	↑	Not Described	none	none
31	Robot/Daihen OTC DR4000 welding	2015	27,420	Leather Good and Allied Product Manufacturing	Manually controlled welder, welding fixtures, deburrer	Welding in awkward positions repetitively. Sometimes employees must weld on their back or knees. Hand intensive work with repetitive motion.	19.0	10.7	↑	Acceptance	Foreign Body, Eye (1) Open Wounds (1)	Rubbed or abraded by friction or pressure (1) Struck by object or equipment (1)

case study (key)	technology classification/specific intervention	year	cost (2016 USD)	Industry	Problematic Process	Employer Description of Risk Factors #	Back/Legs risk - %tile reduction	Upper Extremity risk - %tile reduction	effect on productivity	Employee acceptance	injuries preventable by the intervention (category)	injuries preventable by the intervention (event/exposure)
32	Automated/Weld controlling	2013	26,133	Fabricated Wire Product Manufacturing	High-speed vertical pedestal sander (abrasive belt polisher)	Employees polish 400 parts per hour equating to 30,000 wrist movements per week. Exposures include hands and wrists flexing and extending repeatedly, soft tissue compression, rotating forearms and twisted and unsupported backs, vibration from the sanding belt motion, and pinching and gripping the part. Pressure applied to hold the part against the sanding belt.	14.6	5.4	↔	Not Described	Soft tissue/ Enthesopathy (1)	Overexertion and bodily reaction, unspecified (1)
33	Robot/Universal Robots UR5	2015	85,063	Electroplating, Plating, Polishing, Anodizing, and Coloring	Manually hold work piece in chemical bath for selective plating	Operator constantly holds the work piece with awkward hand placement and the forearm flexed. This process is very repetitive in nature and creates a great deal of fatigue for our operators. Employees must turn their head frequently during the plating process. Some pressure force must be applied to the work piece against the anode during the plating process as well.	14.6	2.5	↑	Acceptance	none	none
34	CNC/Plasma cutting	2003	60,560	Plumbing, Heating, and Air-Conditioning Contractors	Manual handling and cutting sheet metal	Risk factors of awkward postures, forceful exertions, contact stress and repetitive motions (low-moderate) are present in the cutting and notching tasks. Ulnar deviation while holding snips/shears. Forceful exertion to cut metal, contact stress on fingers from the handles			↑	Not Described	none	none
35	CNC/Lathe	2004	314,774	Fabricated Pipe and Pipe Fitting Manufacturing	Operation of manual pipe threading machines	Identical or similar motions performed every few seconds; pinching more than 2 lbs; gripping more than 10 lbs; neck twisting/bending; forceful gripping with the fingers to hold an object; localized vibration; shoulder unsupported with arm above mid-torso height; mild forward or lateral bending.			↑	Not Described	Contusion (1) Fracture - lower extremity (1) Fracture - upper extremity (1) Open Wounds (6) Soft tissue/Enthesopathy (1) Sprains - Neck (1) Sprains - other (1) Sprains - upper extremity (1) Sprains-Back (4)	Caught in or compressed by equipment or objects (2) Contact with objects and equipment, unspecified (1) Other exertions or bodily reactions (1) Overexertion involving outside sources (6) Struck against object or equipment (3) Struck by object or equipment (4)
36	CNC/Plasma cutting	2004	60,989	Plumbing, Heating, and Air-Conditioning Contractors	Cutting and notching sheet metal using sheers, notching machine and snips.	Risk of airborne pieces of metal has been the cause of two eye injuries. Another exposure is Carpal Tunnel Syndrome due to the squeezing of snips and repetitious actions during the cutting and folding process of manual layout.			↑	Not Described	Foreign Body, Eye (1) Open Wounds (2)	Contact with objects and equipment, unspecified (1) Struck by object or equipment (2)
37	Automated/Demolding (Rubber)	2004	59,273	Rubber Product Manufacturing	Operator tends rubber injection molding machine - demolding parts	The demolding operation exposes the operator to smoke from the vulcanization process which has irritated some operators, though minimal chemical exposure risks are present. The majority of the risk is physical - crush forces ranging from 70 to 550 tons and temperatures ranging 340°F to 425°F.			↓	Not Described	none	none
38	Automated/Forming (Sheet metal - ducts)	2004	282,021	Plumbing, Heating, and Air-Conditioning Contractors	Sheet metal fabrication stations and use of flat sheet metal stock	Because of the size and weight of flat stock sheets handled, fabricators experience continual strain on the back, shoulders, legs and arms. Sharp edges and corners expose workers to lacerations and puncture wounds.			?	Acceptance	Contusion (1) Crushing Injury (2) Fracture - upper extremity (1) Open Wounds (4) Sprains - upper extremity (1) Sprains-Back (3)	Caught in or compressed by equipment or objects (3) Overexertion involving outside sources (4) Struck against object or equipment (2) Struck by object or equipment (3)
39	CNC/Punching, shearing	2005	89,175	Metal Service Centers and Other Metal Merchant Wholesalers	Steel punch, drill and shear equipment and associated manual handling	Physical demands to push, pull, maneuver the heavy steel into place weighing in excess of 100 lbs. Awkward positions to hold the steel in place, thus exposing employees to the potential hazards of tripping, or falling into the path of other work being performed. Pinched fingers, cuts or lacerations are common due to the manual manipulation of heavy steel and sharp edges.			↑	Not Described	none	none
40	Automated/Forming (Sheet metal - ducts)	2004	606,264	Plumbing, Heating, and Air-Conditioning Contractors	Manual sheet metal coil feeding equipment	The weight, awkwardness, and sharpness of the sheet metal has potential for a back injury or lacerations. We are lifting 200 – 400 pieces with various weights. Rolls of insulation weighing 30 lbs must be lifted overhead and placed on a rod. The insulating duct requires the lifting that could weigh as much as 80 lbs. Cutting insulation with a razor knife. Potential hazards - possibility of inhaling fiberglass from the insulation or the solvent in the glue, and lacerations due to cutting with a razor knife.			↑	Not Described	Cellulitis or abscess (1) Open Wounds (1)	Overexertion involving outside sources (1) Struck against object or equipment (1)
41	Automated/Molding	2005	127,692	Aluminum Foundries (except Die-Casting)	Mold "squeezer table" and air driven ram.	Lifting portions of the mold weighing 50–100 lbs, 100–150 times every day. As a result, there is a great deal of strain on the fingers, wrists, arms, shoulders, and back.			↓	Not Described	Disc Disorders (1) Soft tissue/ Enthesopathy (1)	Overexertion involving outside sources (2)
42	CNC/Routing	2005	192,735	All Other Plastics Product Manufacturing	Hand held air saws and grinders	Potential for back injury due to the operator having to constantly move, flip and rotate small to very large parts while cutting off excess run out material. These operations also include the potential for carpal tunnel syndrome from repetitive motions. There is vibration exposure and the possibility of deep lacerations or amputation of fingers from the air saw or grinder.			↑	Not Described	Contact Dermatitis and other eczema (1) Contusion (1) Foreign Body, Eye (2) Fracture - upper extremity (1) Open Wounds (2)	Exposure to other harmful substances (1) Falls on same level (1) Struck by object or equipment (5)
43	Automated/Palletizing	2005	179,023	Bottled Water Manufacturing	Manually moving bottled water from conveyor to boxes and manually loading/stacking on pallet	Pallets (30 lbs) are manually stacked then lifted from different heights and carried to the stocking area. Over 70 pallets are handled per day. Boxes weighing 48 lbs are stacked which requires awkward postures. Exposures include back strain, twisting and bending, slips, trips, and falls, as well as cuts and abrasions.			↓	Not Described	Sprains-Back (1)	Other exertions or bodily reactions (1)
44	Robot/Fanuc M-16	2006	132,543	Automotive Seating Manufacturing	Hand-held steam iron	There is a severe risk of injury to the wrist, neck and back while performing this job. The shoulders and elbows show a potential for injury.			↑	Not Described	Soft tissue/ Enthesopathy (3) Sprains - upper extremity (1)	Overexertion involving outside sources (2) Repetitive motions involving microtasks (2)

case study (key)	technology classification/specific intervention	year	cost (2016 USD)	Industry	Problematic Process	Employer Description of Risk Factors #	Back/Legs risk - %tile reduction	Upper Extremity risk - %tile reduction	effect on productivity	Employee acceptance	injuries preventable by the intervention (category)	injuries preventable by the intervention (event/exposure)
45	Robot/ABB M94-A Model 4400	2007	109,524	Metal Service Centers and Other Metal Merchant Wholesalers	Operator tends die cast machine	Risk factor is the repetitive use of the same hand. This is a potential liability to rotator cuff strain, sprains and/or rotator cuff tears. This also could be a problem with back sprains and strains.			↑	Not Described	Burn (7) Soft tissue/ Enthesopathy (1) Sprains - upper extremity (2)	Exposure to temperature extremes (7) Overexertion involving outside sources (2) Slip or trip without fall (1)
46	Robot/Fanuc 420	2006	161,304	Metal Service Centers and Other Metal Merchant Wholesalers	Operator tends die cast machine	Bums from bursting biscuit, hot tooling, and handling hot die castings. Ergonomic hazard associated with repetitive motion, repetitive lifting, twisting and hand squeezing. Possible pinch point areas.			↑	Not Described	Burn (1) Disc Disorders (1) Foreign Body, Eye (1) Sprains - upper extremity (2) Sprains-Back (1)	Exposure to temperature extremes (1) Other exertions or bodily reactions (1) Overexertion involving outside sources (3) Struck by object or equipment (1)
47	Robot/Ranger RT-1000S3	2007	64,602	Plastics Product Manufacturing	Operator tends plastic injection molding machine	The gate is manually opened 550 times in an 8 hour shift. This involves gripping and pulling the handle of the heavy gate. Once all parts have been extracted from the mold the hand and wrist have to be manipulated into different positions to trim the gate using a set of plastic cutters. This will eventually lead to Cumulative Trauma Disorder.			?	Not Described	Sprains - lower extremity (1)	Slip or trip without fall (1)
48	Automated/Insertion	2007	47,060	Fabricated Structural Metal Manufacturing	Use of brake press to press PEM nuts/studs into sheet metal	The main risk factor created by this job is the strain which is created on the lower back from bending in the 90 degree position while the neck is tipped up to assure proper alignment of the PEM nuts. Secondary risk factors are the strain created on the arm, shoulder, and neck area from reaching excessively and forcefully turning the part. This is done 25 hours per week.			↑	Acceptance	none	none
49	Robot/Star LW-1000V-460	2007	51,345	Plastics Product Manufacturing	Use of Snips to cut away parts	Exposure to a sharp cutting device. Poor hand posture can create fatigue and could lead to cumulative trauma injuries. Repetitive cutting of the parts does lead to neck, shoulder and arm fatigue in addition to the complaints of hand symptoms.			↑	Not Described	Open Wounds (1)	Struck by object or equipment (1)
50	Robot/Fanuc s-430iW	2008	70,903	Metal Tank Manufacturing	Manual handling of tank heads.	The machine configuration leads to poor ergonomics which can lead to potential back and abdominal injuries. Having to lean into the press with arms outstretched poses a risk for injury. Moving tank heads by hand raises the risk of a part (weighing up to 90 lbs) slipping and being dropped. which could result in a broken hand or foot. Overhead reaching to activate press palm controls.			↑	Acceptance	Hernia of abdominal cavity (1)	Overexertion involving outside sources (1)
51	CNC/Press brake, shearing, grinding (multi)	2009	67,384	Saw Blade and Handtool Manufacturing	Hydraulic bending machine; use of an abrasive chop saw to cut bar stock	The inherent risks associated with these operations include cuts/abrasions, strains/ sprains, contact in pinch points, flying particles, amputation, noise and dust. Strains/ sprains from multiple tooling changes and crushed fingers and fractures from tooling changes and contact in pinch points since there is no way to guard this equipment effectively,			?	Not Described	Fracture - upper extremity (1)	Struck by object or equipment (1)
52	CNC/Plasma cutting	2010	68,349	Machine Shops	Cutting and shaping metal using vertical and band saws; acetylene torch; and hand grinders.	Employees use a hand held torch to cut material. Exposures include flash burns, falling debris or parts, and risk of being cut on the jagged edge. Common complaints are of fatigue and pain in the lower back and neck due to bending and reaching across part.			↑	Not Described	none	none
53	CNC/Lathe	2010	198,014	Other Nonferrous Metal Foundries (except Die-Casting)	Older lathes and other equipment	Exposure to continuous heavy loads some of which are in the 75 lb range and are of awkward shape. Exposure to repetitive arm, hand and shoulder motion and vibration. Exposure to vibration can also cause the operator to grip the parts or machine lever with greater force, putting extra strain on the hand and fingers. The manual lathes require the operator to use awkward body positioning to load and unload parts as well as operate the machinery. These positions involve raising one's arm above shoulder height. Repetitive unloading and loading of parts into machine chuck.			↑	Not Described	none	none
54	Automated/Coil winding	2013	68,422	Power, Distribution, and Specialty Transformer Manufacturing	Wire is pounded into place with rubber mallets in the process of coil winding	Repetitive hammer hits - 30 to 40 hammer hits for each layer in about a 3–5 minute period. The motion from swinging the mallet exposes the operator to stress and fatigue, which could result in repetitive motion injuries. Winding employees are utilizing rubber mallets that weigh 21, 42, 52, and 96 ounces.			?	Not Described	Burn (1) Contusion (1) Fracture - upper extremity (1) Open Wounds (1) Soft tissue/Enthesopathy (1) Sprains - upper extremity (2)	Caught in or compressed by equipment or objects (2) Exposure to temperature extremes (1) Overexertion involving outside sources (2) Struck by object or equipment (2)
55	Robot/Fanuc R-2000	2014	74,357	Wood Container and Pallet Manufacturing	Layout of material and use of pneumatic nail gun in assembly of wood crates	Persistent use of a nail gun poses risks of carpal tunnel syndrome. Long time exposures to a panel jigging system poses potential physical hazards such as lumbar injuries, strain/sprain on shoulder, upper arm, rotator cuff, radius/ulna or wrist.			↑	Acceptance	none	none
56	Robot/Yaskawa Motoman custom	2014	162,510	Chocolate and Confectionery Manufacturing	Hand tying ribbons on small boxes	Repetitive motion of right arm pulling down ribbon. Continuous movement of fingers and wrists. Long periods of time sitting for lower back fatigue. Lifting 1 lb boxes with above waist extremities while sitting. 1000 bows are tied per employee per 10 hour shift.			↑	Not Described	none	none
57	Robot/Fanuc R-2000	2014	68,964	Plastic Products Manufacturing	Manually placing and removing inserts from a mold cavity	The repetitive motions of forceful grabbing, reaching and pushing over 600 times per shift to insert the components into the mold cavities and needing to look down and side to side each time, has the potential for strain/sprains of the shoulders, back, arms, wrist, and neck, bilateral epicondylitis, carpal tunnel.			↑	Acceptance	Open Wounds (1)	Struck by object or equipment (1)
58	CNC/Routing	2014	58,574	Wood Cabinet Manufacturing	Table saw, drill press, jig saw and handheld router	Processes for cutting, carving, drilling and machining wood and other materials require employees to lift, position, hold and feed the material into or onto the table saw, drill press, jig saw and handheld router; and to transfer the pieces between tools. The 82 lb. boards are likely considered a Medium to High Risk lifting task given there are two people lifting and because the lift is from knee height to waist height.			↑	Acceptance	none	none

case study (key)	technology classification/specific intervention	year	cost (2016 USD)	Industry	Problematic Process	Employer Description of Risk Factors #	Back/Legs risk - %tile reduction	Upper Extremity risk - %tile reduction	effect on productivity	Employee acceptance	injuries preventable by the intervention (category)	injuries preventable by the intervention (event/exposure)
59	Automated/Bottling	2015	131,194	Distilleries	Manual handling during bottling, capping and labelling	The bottlers have to move the bottles down the line requiring a great deal of repetitive motion that can lead to repetitive stress injuries to the hands, wrists, elbows and shoulders. Hand intensive work with lifting			↑	Acceptance	Open Wounds (1)	Struck by object or equipment (1)
60	Robot/Fanuc M20	2015	50,626	Machine Tool Manufacturing	Deburr wheel and laser etching machine	The operator is holding pieces of aluminum in front of a deburr wheel for their entire shift. Hand intensive work with repetitive motion and vibration exposure with very small parts and detailed contoured edges. The other operator loads and unloads the laser machine with parts which is also hazardous because of the danger of catching the laser in the operator's eye.			↔	Acceptance	Contact Dermatitis and other eczema (1)	Exposure to other harmful substances (1)
61	Robot/Universal Robots UR10 (collaborative robot application)	2015	55,984	Precision Turned Product Manufacturing	Manually tend CNC lathe with high production rate	Highly repetitive hand movements and grip/grasp motions. This highly repetitive environment contains hazards that could result in work related injury and illness such as Carpal Tunnel Syndrome and Tendonitis.			↑	Acceptance	none	none
62	CNC/Drilling (Wood)	2016	58,374	Transportation Industry Roll Up Door Manufacturing	Manual placement of hinges and drilling	Numerous strain issues with the person under the door in very awkward positions for several hours per day. Neck from bending to look up at door. Shoulders from working with hands above shoulder height. All areas of the back from awkward postures and wrists are severely bent when drilling holes. Grip hazards with vibration from holding power drill.			↑	Not Described	Sprains - upper extremity (1)	Caught in or compressed by equipment or objects (1)
63	CNC/Edgebanding	2016	103,619	Wood Kitchen Cabinet and Countertop Manufacturing	Manual cutting, joining and glueing tools.	Many awkward postures of the shoulders, lower back and neck. Risk factors observed include: back flexion, shoulder flexion/extension between +/−30 degrees on the right side and static posture with downward pressure applied by the left hand/arm to steady the board. Elbow flexion and static abduction of the right arm to operate the air gun. Risk factors observed include: pivoting the right shoulder using abduction and adduction and moving the right hand/wrist 16 times to spray glue during a 14 second period. Neck flexion in a static posture is used during spraying.			↑	Acceptance	none	none

#(Employer description is paraphrased, but closely represents language used by the employer.)

↑ increased, ↓ decreased, ↔ unchanged, ? not described

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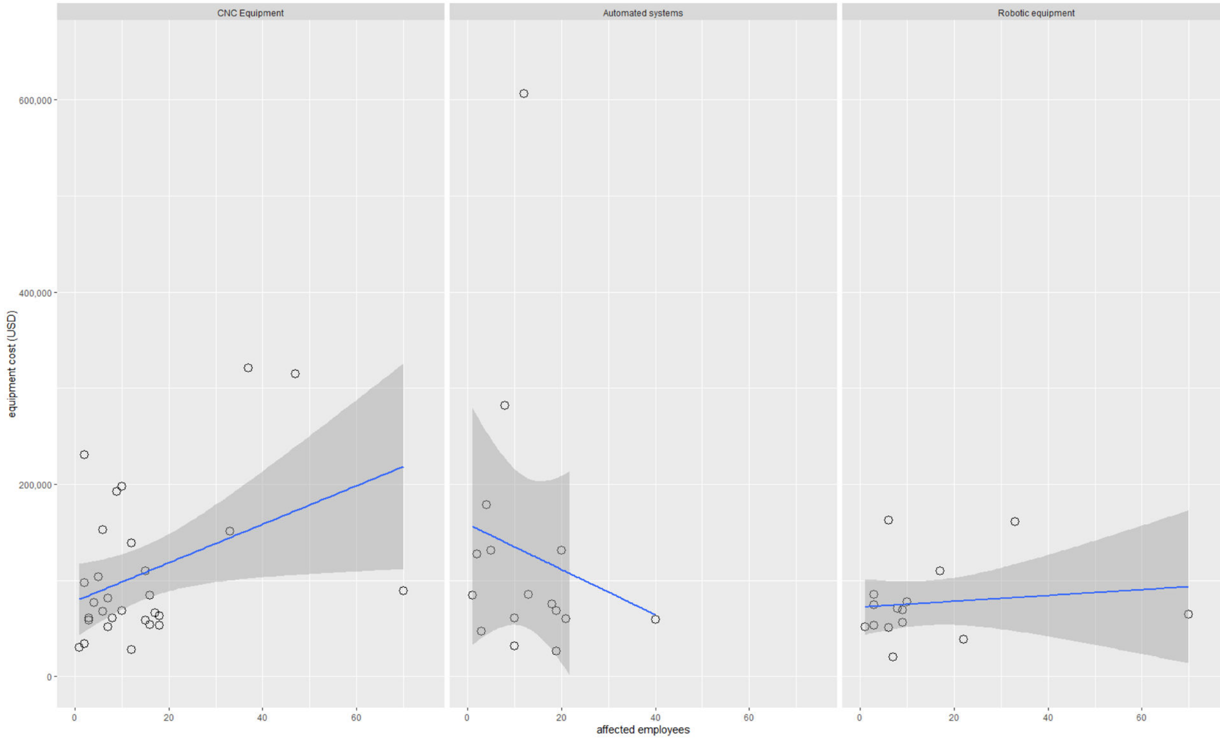
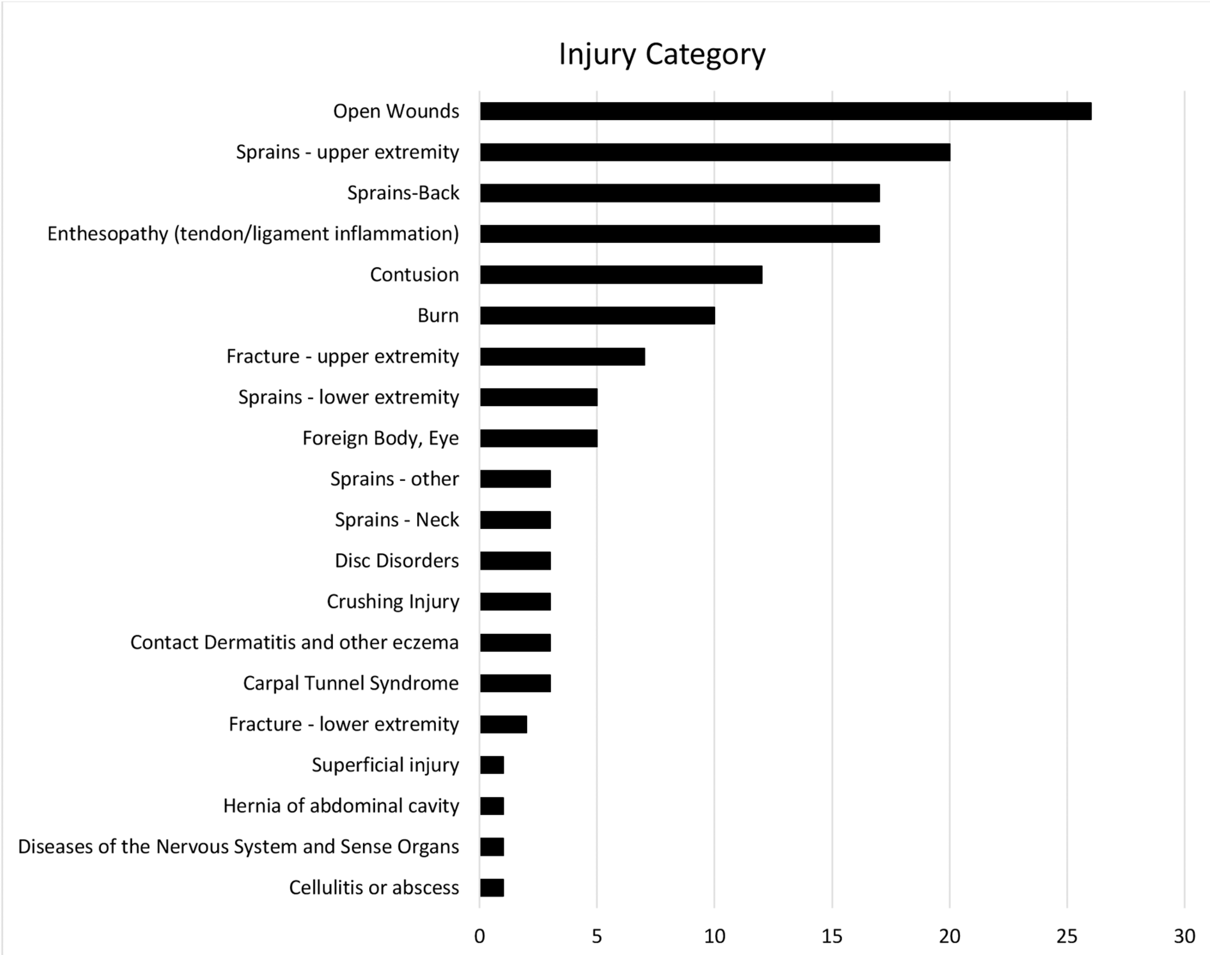


Figure 1.
Intervention equipment costs (2016 USD) and number of employees affected by the intervention. Three grants (described in note to Table 1) were removed from the plots as outliers on cost or affected employee count.


Injury Category
Open Wounds
Sprains - upper extremity
Sprains-Back
Enthesopathy (tendon/ligament inflammation)
Contusion
Burn
Fracture - upper extremity
Sprains - lower extremity
Foreign Body, Eye
Sprains - other
Sprains - Neck
Disc Disorders
Crushing Injury
Contact Dermatitis and other eczema
Carpal Tunnel Syndrome
Fracture - lower extremity
Superficial injury
Hernia of abdominal cavity
Diseases of the Nervous System and Sense Organs
Cellulitis or abscess
0
5
10
15
20
25
30

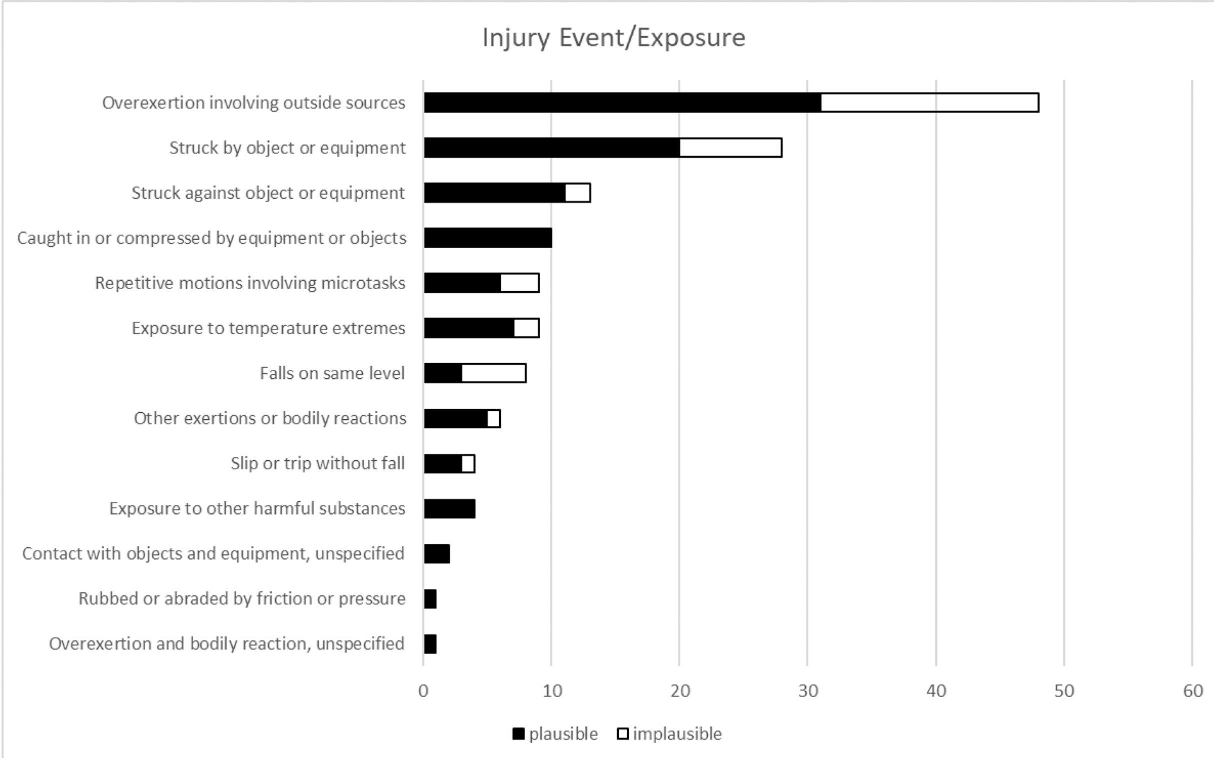


Figure 2.

(a) Category of injuries for N = 143 workers' compensation (WC) injury claims in two-year baseline periods preceding the intervention. (b) Injury event/exposures for same WC injury claims. Dark shading indicates investigators' determinations as to whether the equipment intervention could have plausibly prevented the injury event/exposure.

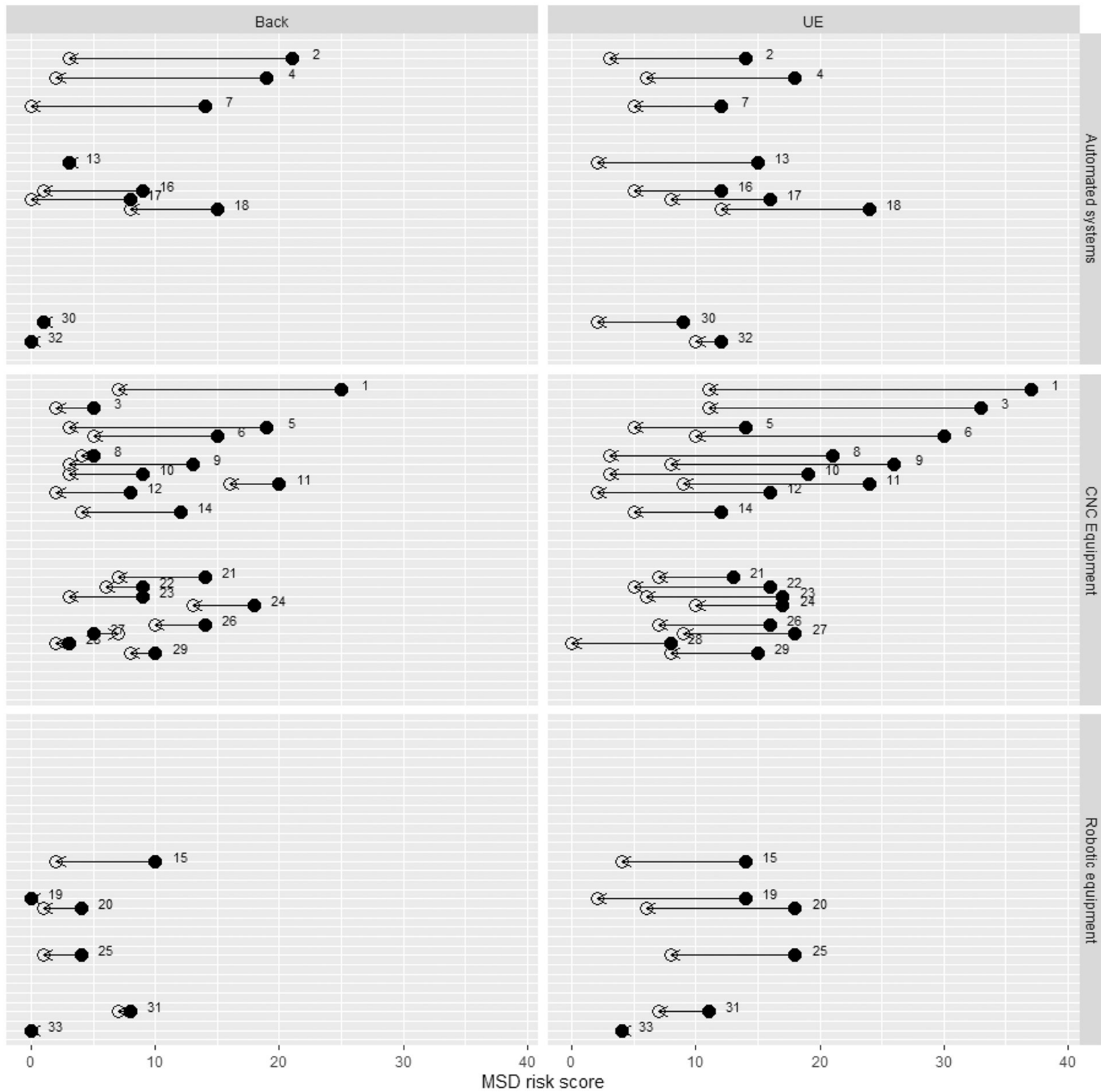


Figure 3.
Reductions in Back and upper Extremity (UE) MSD risk factor scores for case studies with quantitative assessments (n = 33). Pre-intervention score = ●; post-intervention score = ○. Case study reference numbers refer to Appendix 1.

Table 1.

Summary of Safety Intervention Grant expenditures and affected employees by equipment technology category. (USD = United States Dollars)

Equipment Classification	No. of case studies	Sum of affected employees	Equipment Cost (2016 USD)	Avg affected employees/case study	Avg cost per case study (2016 USD)	Cost/Affected employee (2016 USD)
Industrial Robots *	15	207	1,165,174	13.8	77,678	5,629
CNC Machines	29	411	3,097,845	14.2	106,822	7,537
Automated Systems **	16	205	2,055,382	12.8	128,461	10,026

Note: summary includes 60 of 63 case studies.

* Excludes two case studies (#15, #44) with number of affected employees documented by employer as 155 and 216. See text description.

** Excludes one case study (#4) with equipment cost of $5.175 million (2016 USD).