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RESEARCH ARTICLE

Robot-Related Workers' Compensation Claims in Ohio, 2001–2020

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ABSTRACT

Background: Increased robot adoption and advancements in robotics have led to the emergence of robotic arms for collaborative applications that work alongside humans, increasing direct human-robot interaction. This shift highlights the need to address new safety challenges posed by emerging robotic technologies. Currently, there is limited research on robot-related injuries.

Methods: Robot-related workers' compensation claims from 2001 to 2020 were identified using a keyword search from the Ohio Bureau of Workers' Compensation (OHBWC) database. Descriptive analyses were conducted on this claims dataset.

Results: From 2001 to 2020, 1076 robot-related claims were identified, with 85% medical-only claims (medical care only and/or $\leq$ 7 days away from work). Most claimants were male (74.2%), and 51.1% were 25–44 years old. More than half of the claims were due to contact with objects and equipment (57.9%), followed by overexertion and bodily reaction (20.6%). Most injuries occurred in the manufacturing sector (75.1%), followed by the service sector (14.7%). The claims resulted in over $8.3 million in costs. Of this figure, 91% was incurred due to lost-time claims ($7.6 million). Almost 30% of claims included diagnoses from multiple diagnosis groups. Most claims involved working with robotic arms for collaborative applications (75.7%) in a shared workspace.

Conclusions: Robotics is rapidly evolving to remove workers from hazardous environments and reduce risks from hazardous, repetitive, and manual tasks, but it may introduce new workplace hazards. There is a need to study robot-related injuries, identify high-risk exposures, and develop sector- or application-specific comprehensive safety approaches for safer implementation of robots in the workplace.

1 | Introduction

Industrial robots were introduced in the U.S. workplace in the mid- to late-twentieth century, with the earliest applications primarily in the automobile manufacturing sector for die casting, spot welding, and material handling [1–3]. The adoption of robots in industry has been rapidly increasing ever since. Globally, the annual count of industrial robots installed increased from 50,000 to 400,000 from 1993 to 2017 [4]. Advancements in science and technology have led to rapid evolvement in the field of robotics. The next generation of professional and personal/domestic service robots emerged in the early 21st century, with primary applications including

Institutions at which the work was performed: National Institute for Occupational Safety and Health, Ohio Bureau of Workers' Compensation.

inspection and maintenance (Laser Guided Vehicles [LGVs], Automated Guided Vehicles [AGVs], Unmanned Aerial Vehicles [UAVs], recreation, education, and research) [5]. The latest range of robots, robotic arms for collaborative applications, perform tasks alongside or in close contact with workers, sharing a common task or workspace. The rapid technological developments in the field of robotics are also reflected in their expanding range of work environments and in the changing definitions of robots to accommodate these emerging technologies [5]. Additionally, with growing adoption of robots across industry sectors, workers may experience increased direct or frequent contact with robotic arms and mobile robots, highlighting the potential value of understanding new safety challenges and opportunities for prevention [6].

There is a wide range of potential implications for implementing robots in the workplace. A recent study conducted by Lowe, Hayden, Albers and Naber [7] reviewed 63 case studies documenting the effects of robots as health and safety interventions in small manufacturing enterprises. A German-based study found evidence for robot exposure leading to a 4% and 5% decline in physical job intensity and disability, respectively [8]. In most cases, manufacturing automation improved processes and worker productivity, reduced risk factors associated with musculoskeletal disorders, and lowered the cost per affected employee [8]. While introducing robots in the workplace decreased some hazardous occupational exposures by performing tasks that are repetitive, monotonous, or pose higher risk exposures to workers [9] they can also potentially introduce new hazards in the workplace. The first robot-related death was reported in the United States in 1979 [10]. The Census of Fatal Occupational Injuries (CFOI) reported 41 robot-related fatalities during the period from 1992 to 2017 [5]. Most deaths occurred due to struck-by or crushing incidents [11, 12]. According to U.S. Occupational Safety and Health Administration (OSHA) Severe Injury Reports (SIRs), 77 robot-related incidents led to severe injuries during the period from 2015 to 2022, underscoring gaps in controls such as guards and collision-avoidance systems [12]. Recent research in the international/global realm provides evidence for an increased rate of occupational injuries in the initial years of integrating robot applications into industries in developing countries, followed by a rate decline in later stages through safety regulations [11–13]. As robots become increasingly commonplace in industrial, commercial, and social settings, so does the potential for robot-related injuries in the workplace [6, 14]. Combining proactive and reactive control measures may support safe human-robot interactions (HRIs) in the future.

Robot safety standards, such as American National Standards Institute/Robotics Industries Association (ANSI/RIA) R15.06 and R15.08 [15–18] exist to help minimize workplace injuries, enhance operational safety, and improve productivity in industrial sectors. Established by the Association for Advancing Automation (A3) in 1982, the R15.06 standard laid the foundation for industrial robot safety in the U.S., evolving through systematic frameworks that emphasize risk assessment and hazard mitigation. Key updates, such as the 1999 edition's structured hazard assessment framework and the 2012 alignment with the International Organization for Standardization (ISO) 10218 [19–22] streamlined compliance for global manufacturers, strengthened safeguarding measures, and introduced guidelines for robotic arms for collaborative applications to work safely alongside humans. The ANSI/A3 R15.08 standard addresses the unique safety challenges posed by industrial mobile robots, focusing on mitigating risks associated with their operation and interaction with human workers. Together, these standards serve as resources for manufacturers, system integrators, and end-users, ensuring that the benefits of robotic technologies are realized without compromising safety or operational efficiency in modern manufacturing environments.

Since 1987, seven studies in the U.S., Germany, Japan, Sweden, South Korea, and Finland have evaluated robot-related fatalities and injuries with the goal of identifying risk factors and the cause of injury or death [5, 8, 11, 23–26]. While the major focus of these studies was on gaining safety insights through fatality assessments and investigations, fewer studies assessed robot-related injuries in the workplace in the U.S [5, 12]. A study by Sanders et al. identified 77 robot-related injuries during the period from 2015 to 2022 using OSHA's Serious Injury Reports [12]. The study identified hazards that led to robot-related incidents and described the injury type, event, and post-collision mitigation strategies. However, detailed information on robot types, operating conditions, and specific robot hazards was not examined in those studies. Thus, the National Institute for Occupational Safety and Health (NIOSH) Center for Occupational Robotics Research (CORR), which was established to address the safety of workers who use, wear, or work near robots, highlighted the role of surveillance and monitoring of injuries related to emerging technologies like robotics and automation to improve workplace safety.

This study used claims data from the Ohio Bureau of Workers' Compensation (OHBWC) from 2001 to 2020 to identify and describe robot-related injuries and their costs. Workers' compensation (WC) claims offer detailed information about injured workers, including the cost, severity, and nature of the injury, along with narratives describing the events and exposures that led to the injury. This study aimed to quantify risk exposures, identify emerging health and safety concerns, and enhance injury prevention through WC claims surveillance. Additionally, this study sought to identify industry-specific safety priorities to help mitigate worker injuries and illnesses related to robot incidents in the workplace [27]. Several studies have used the OHBWC claims data to identify risk exposure and prevent injuries, illnesses, and fatalities in multiple sectors, including construction, landscaping, and law enforcement [28–30]. However, robot-related WC claims in the U.S. have not yet been explored. This study builds on the previous body of robot-related injury research by broadly exploring the largest dataset of robot-related injury claims to date (1076 OHBWC claims).

2 | Methods

2.1 | Data Source

The OHBWC is the largest state-run WC system in the United States. The system covers more than 250,000 public and private employers [31] and insures approximately two-thirds of workers in Ohio. All employers, except sole proprietorships and partnerships, are expected to be insured by OHBWC. However, some employers have the option to be insured by OHBWC or choose self-insurance, provided they demonstrate financial stability in covering WC and medical costs for work-related injuries [31].

2.2 | Claims Data

NIOSH partnered with the OHBWC to analyze WC data for research and surveillance of occupational injuries in Ohio [31]. The data include information on various characteristics such as demographics (sex, age group), establishment size, industry description, diagnosis codes, free-text occupation title, and a brief free-text narrative (1–3 sentences) for each claim describing the circumstances of the injury or illness. Claims are defined as medical-only (MO) or lost-time (LT) by OHBWC [31, 32]. MO claims cover only the medical treatment expenses associated with a workplace injury and may include situations where the injured worker is off work for 7 days or fewer without any wage loss benefits being paid. In contrast, LT claims involve injuries that result in the worker being unable to work for 8 or more days, and these claims include wage compensation for the duration of the worker's absence. These claims are considered more severe than MO claims.

Industry descriptions were coded by the North American Industry Classification System (NAICS) and assigned to the corresponding National Occupational Research Agenda (NORA) sector by NIOSH [33]. Using incident narratives, one- and two-digit event or exposure codes were assigned based on the Bureau of Labor Statistics (BLS) Occupational Injury and Illness Classification System (OIICS), version 2.01 through a machine-learning auto-coder developed by NIOSH [34]. The major event or exposure categories include violence and other injuries by persons or animals; transportation incidents; fires and explosions; falls, slips, and trips; exposure to harmful substances or environments; contact with objects and equipment; and overexertion and bodily reaction. In this study, overexertion and bodily reaction events include activities such as lifting or handling robotic equipment or components, pushing or pulling robotic equipment, and repetitive or forceful movements while loading or unloading parts during routine work with a robot, resulting in muscle strain or back pain.

A set of 57 mutually exclusive clinical diagnosis groups was developed by OHBWC and NIOSH using the diagnosis codes from the International Classification of Diseases, Ninth and Tenth Revision, Clinical Modification (ICD-9-CM, ICD-10-CM) for analysis of OHBWC claims data [27]. These clinical diagnosis groups were systematically designed and aligned with ICD structure, enabling analysis of WC data across coding transitions [27]. Each clinical diagnosis group was counted once per claim; however, a single claim could include multiple distinct diagnosis groups. For example, a worker might have a back sprain and an open wound from the same incident. In this study, clinical diagnosis groups with fewer than five cases were collapsed into an "All other" category. Occupation was coded using the NIOSH Industry and Occupation Computerized Coding System (NIOCCS), a tool designed to automate the classification of free text into standardized codes [35]. The 2018 BLS's Standard Occupational Classification (SOC) system was then applied to assign 6-digit-level SOC codes for occupations [36].

WC claims data include costs associated with six disability classifications based on the severity and impact of a work-related injury or illness [31]. These classifications include death, permanent total disability (PTD), permanent partial disability (PPD), permanent partial and temporary total disability (PPTTD), temporary total disability (TTD), and MO. PTD applies when a worker is permanently unable to return to any form of work (e.g., paralysis from a spinal cord injury). PPD involves lasting impairments that reduce work capacity but still allow the ability to work (e.g., loss of vision in one eye). PPTTD refers to injuries that cause both a temporary inability to work and a permanent partial impairment (e.g., a leg fracture requiring surgery and resulting in long-term limited mobility). TTD covers cases where a worker is temporarily unable to work but is expected to recover and return to their job (e.g., a hand fracture). Some claims have zero cost in the OHBWC database because no medical treatment was provided [31]. Thus, cost analysis was performed for total costs including all claims and total costs excluding zero-cost claims, with results reported for both the mean and median. The WC claim costs presented in this analysis were not standardized or adjusted to a single timepoint because the analysis focused on cost comparisons across injury events, claim severity, and industries rather than estimates of inflation-adjusted costs. The costs include payments for medical care, indemnity (partial wage replacement), and reserves for anticipated future payments as of July 2023.

2.3 | Identification of Robot-Related Cases: Keyword Search and Coding

A comprehensive keyword search was conducted, identifying 2399 potential robot-related claims based on specific keywords (listed in Appendix, Table A1). Keywords "robot," "auto," "autonom," "mate," "laser," "exoskel," "bionic," "drone," "machine," and their variations were used to identify potential robot-related claims. Examples of variations of keywords used include "manipulator," "effector," "cobot," "LGV," "AGV," "automat," "unmanned aircraft," "mechanical arm," and so on (Appendix, Table A1).

We followed a stepwise process to identify and characterize robot-related WC claims. Each claim's incident narrative was manually reviewed by three independent reviewers to verify the involvement of a robot using a 5-point classification scale ranging from "definitely robot-related" to "definitely not robot-related" (Figure 1). Three reviewers examined each claim description and supplementary information to determine robot involvement. If claims were coded as 1 (definitely robot-related) or 2 (probably/mostly robot-related) by all three reviewers, they were included for analysis without further review. Claims coded as 4 or 5 were excluded, whereas those coded as 3 (uncertain) were subjected to additional collaborative review to reach a consensus. Ultimately, 1076 of the 2399 initially screened claims (44.9%) were confirmed as robot-related and included for analysis (Figure 1).

2.4 | Identification of Robot Type, and Environment

After identifying 1076 robot-related claims from the OHBWC dataset, a qualitative review of the narrative incident descriptions was conducted to extract key information about the type of robot involved and its operating environment

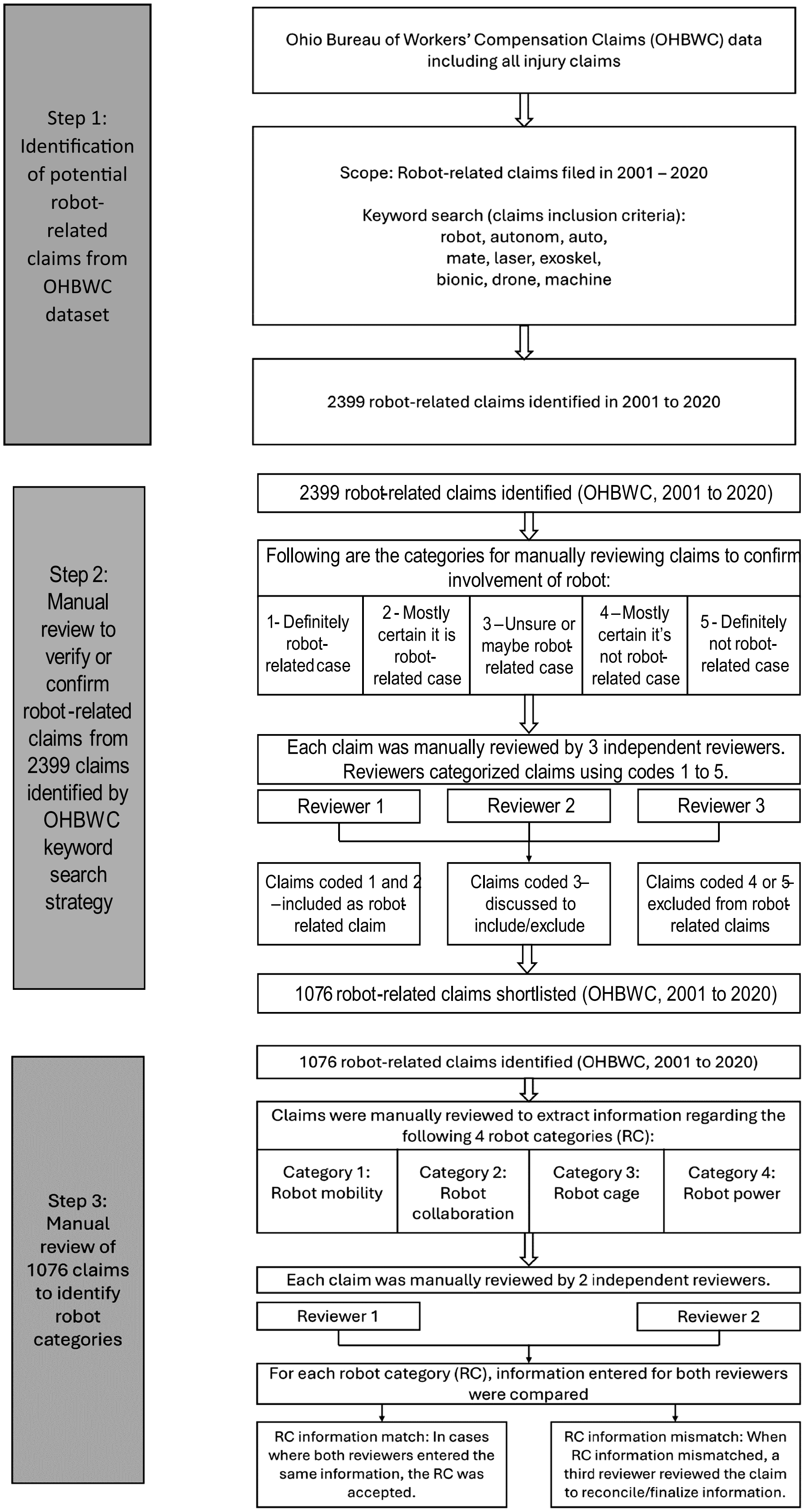

FIGURE 1 | Flow chart explaining methodology of multiple independent reviewer process for robot-related case identification and classification.

(Figure 1). For robot type, the review considered mobility and collaboration types, each classified into three predetermined categories (Table 1). The "Robot Collaboration" in robot type referred to cases that involved a collaborative application such as assembly, material handling, quality inspection, and welding, as defined by the ISO 10218 Standard [19]. For the robot environment, the review identified whether the robot was caged or powered at the time of the incident, with each feature also categorized into three levels (Table 1). For the qualitative review, each claim was independently reviewed by two reviewers to determine these features. If incident descriptions lacked sufficient information, reviewers marked those features as "undetermined." A third reviewer examined claims where disagreements occurred between the initial two reviewers on feature categorization. These claims were then reevaluated to reconcile discrepancies and finalize the classifications. As an example of the coding process, one case involved an employee working on an automated guided vehicle who reached underneath for a safety switch and sustained injury when the wheel moved and ran over his hand. This case was coded as "mobile" for robot mobility category, "autonomous" for robot collaboration, and the robot environment as "uncaged" and "powered." Overall, the qualitative review provided insights into robot types and operating conditions, offering a detailed understanding of the factors contributing to robot-related incidents.

2.5 | Analysis

Descriptive analyses were performed to summarize the frequency of claims for demographic, employer, industry, occupation, robot-related characteristics, injury, and claim characteristics, and their associated total costs were also reported. Trends in the number of claims by year and claim type were analyzed using a negative binomial regression model to account for overdispersion.

TABLE 1 | Robot type, environment features and their respective categories.

	Categories
Robot type	
Robot Mobility	Fixed base
	Mobile
	Undetermined
Robot Collaboration	Autonomous/Automatic
	Collaborative
	Undetermined
Robot environment	
Robot Cage	Caged
	Uncaged
	Undetermined
Robot Power	Powered
	Unpowered
	Undetermined

3 | Results

During the period from 2001 to 2020, a total of 1076 robot-related workers' compensation claims were identified, with 85.2% being MO claims ($n = 917$). The majority of the claimants were male ($n = 798$, 74.2%; Table 2). Two age groups, 25–34 and 35–44, together contained more than half of all cases filed during this period ($n = 550$, 51.1%). More claims were concentrated in Northeastern ($n = 369$, 34.3%) and Southwestern ($n = 331$, 30.8%) Ohio. The highest percentage of claims (63.6%) were filed in companies with employee counts in the 100–1000 estimated FTE range ($n = 684$).

The number of claims per year varied considerably, ranging from 29 to 90 claims annually (Figure 2). On average, there were approximately 54 claims per year. From 2001 to 2020, the number of robot-related total claims significantly decreased by

TABLE 2 | Number and percentage of robot-related workers' compensation claims by demographics, region, and establishment size, Ohio, 2001–2020.

Characteristics	Total claim count	Percent of total claims
Sex		
Female	266	24.7
Male	798	74.2
Unknown	12	1.1
Age group		
< 25	172	16.0
25–34	272	25.3
35-44	278	25.8
45–54	228	21.2
55–64	114	10.6
65+	10	0.9
Unknown	2	0.2
Geographic region in Ohio		
Northeast	369	34.3
Northwest	290	27.0
Southeast	23	2.1
Southwest	331	30.8
Unknown	63	5.9
Establishment size (estimated)		
> 0 to 10 FTEs	12	1.1
> 10 to < 50 FTEs	114	10.6
≥ 50 to < 100 FTEs	155	14.4
≥ 100 to < 250 FTEs	313	29.1
≥ 250 to < 1000 FTEs	371	34.5
≥ 1000 FTEs	64	5.9
Unknown	47	4.4
Total	**1076**	**100**

Abbreviation: FTE, full-time equivalent (defined as an employee worked 2000 h annually).

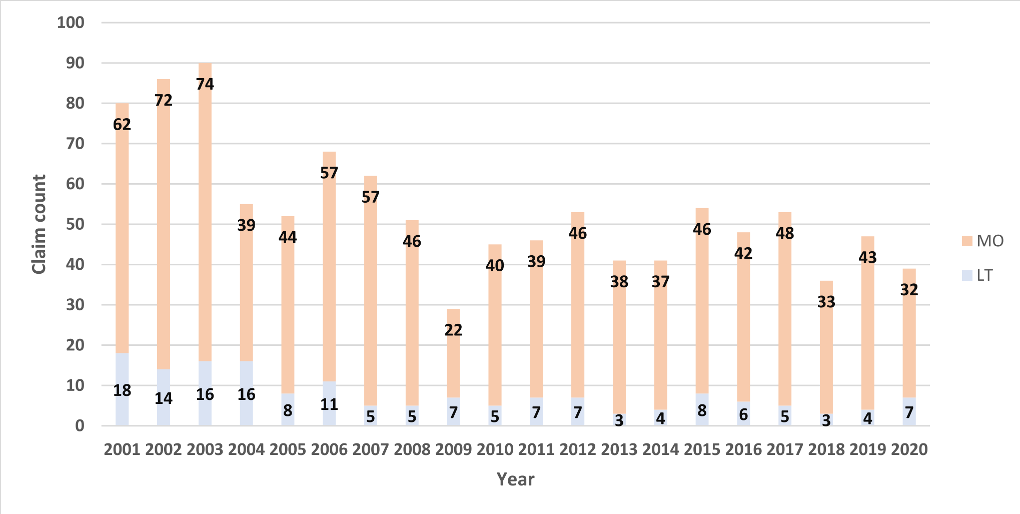

FIGURE 2 | Number of robot-related workers' compensation claims by year and claim type, Ohio, 2001–2020. LT, lost-time (≥ 8 days away from work); MO, medical-only (0–7 days away from work and/or medical treatment). [Color figure can be viewed at wileyonlinelibrary.com]

51% ($p < 0.0001$). LT claims significantly decreased by 61% ($p < 0.0001$), and MO claims decreased by 48% ($p = 0.002$) (Figure 2).

3.1 | Clinical Diagnosis Groups

For the 1076 robotics-related WC claims identified in the study, a total of 1,516 unique clinical diagnosis groups were assigned (Table 3). The majority of claims had a single clinical diagnosis group assigned ($n = 760$, 70.6%), while the remaining 29.4% of claims ($n = 316$) had multiple diagnosis groups assigned ($n = 756$) (data not shown). The five leading clinical diagnosis groups were: open wound ($n = 328$, 21.6%), contusion ($n = 304$, 20.1%), sprain of the upper extremity ($n = 137$, 9.0%), sprain of the back ($n = 96$, 6.3%), and superficial injury ($n = 92$, 6.1%). Together, these top five diagnosis groups accounted for nearly two-thirds of all diagnosis groups (63.1%).

3.2 | Total Claim Costs

During this study period, the 1,076 robot-related claims resulted in over $8.30 million in total costs (Table 4), with an average cost per claim of $7,718. The majority of claims were MO claims, accounting for 85.2% of the total claims ($n = 917$), but which only accounted for 9.0% of the total claim costs ($748,452), with an average claim cost of $816. In contrast, LT claims represented a smaller portion of the total claim count ($n = 159$) at 14.8%. However, they constituted a significant share of the costs, accounting for 91% of the total ($7.56 million), with an average claim cost of $47,526. Among LT claims, temporary total claims were the most common, with 70 claims costing approximately $1.64 million. Notably, permanent total disability claims, although there were only six, accounted for approximately half of the total claim costs at $4.01 million (49.0%) (Table 4).

3.3 | Robot-Related Claims by Injury Event or Exposure

During this study period, more than half of robot-related injuries occurred due to contact with objects and equipment ($n = 623$, 57.9%), followed by overexertion and bodily reaction ($n = 222$, 20.6%), and falls, slips, and trips ($n = 114$, 10.6%) (Table 5). These three events accounted for 89% of all claims. The most common injury event subcategories while working with robots included: being struck by an object or equipment (OIICS code 62; $n = 301$, 27.9%), overexertion involving outside sources (OIICS code 71; $n = 180$, 16.7%), struck against an object or equipment (OIICS code 63; $n = 165$, 15.3%) and caught in or compressed by equipment or objects (OIICS code 64; $n = 144$, 13.4%) (data not shown).

In terms of total costs, injuries resulting from contact with objects and equipment incurred the highest expenses ($3.43 million, 41.3%), followed by injury claims due to falls, slips, and trips ($2.45 million, 29.5%), and overexertion and bodily reaction injuries ($2.25 million, 27.1%) (Table 5). Notably, although falls, slips, and trips accounted for only 10.6% of total claims, they represented 29.5% of the total claim costs. Furthermore, the average cost per claim for falls, slips, and trips was $21,498, which is almost three times higher than the overall average claim cost of $7718.

3.4 | Robot-Related Claims by NORA Sector

From 2001 to 2020, the majority of robot-related claims were filed by workers from the manufacturing sector ($n = 808$, 75.1%), followed by the services sector ($n = 158$, 14.7%) and wholesale and retail trade sector ($n = 58$, 5.4%) (Table 6). Together, these three sectors accounted for 94.7% of all robot-related claims. Within the manufacturing sector, only 13.4% were lost-time claims ($n = 108$), and most claims originated from the motor vehicle manufacturing industry ($n = 291$, 36.0%) and the plastic and rubber manufacturing industry ($n = 137$, 17.0%) (data not shown). Within the services sector, 72.2% of the injury claims ($n = 114$) were from the temporary help services industry. Of these, 86.0% ($n = 98$) involved

TABLE 3 | Number and percentage of robot-related workers' compensation claims by clinical diagnosis groups, Ohio, 2001–2020.

Clinical diagnosis group	Count	Percent
Open wounds, NEC	328	21.6
Contusion with intact skin surface	304	20.1
Sprains - upper extremity	137	9.0
Sprains - back	96	6.3
Superficial injury	92	6.1
Diseases of the nervous system and sense organs, NEC	78	5.1
Soft tissue/enthesopathy	46	3.0
Sprains - lower extremity except knee	46	3.0
Fracture - upper extremity	44	2.9
Sprains - neck	41	2.7
Crushing injury	38	2.5
Burn	36	2.4
Intracranial injury	34	2.2
Other and unspecified effects of external cause, NEC	32	2.1
Foreign body, eye	23	1.5
Sprains - nec	13	0.9
Diseases of musculoskeletal and connective tissue, NEC	12	0.8
Cellulitis or abscess	12	0.8
Carpal tunnel syndrome	11	0.7
Disc disorders and spinal stenosis	10	0.7
Mental, behavioral and neurodevelopmental disorders, NEC	8	0.5
Fracture - head	8	0.5
Fracture - neck and trunk	7	0.5
Fracture - lower extremity	6	0.4
Hernia	5	0.3
Symptoms, signs, abnormal clinical or laboratory findings, NEC	5	0.3
Knee sprain or tear	5	0.3
All other[a]	39	2.6
Total	1516	100.0

Abbreviation: NEC, not elsewhere classified.
[a]injury to nerves and spinal cord; poisoning and toxic effects, medical or non-medical; joint disorders, NEC; mental disorders from brain damage; amputation; contact dermatitis and other eczema; dislocation; diseases of the respiratory system, NEC; fracture – nec; internal or blood vessel injuries, NEC; diseases of the circulatory system, NEC; complications of surgical and medical care, NEC; congenital abnormalities, NEC and perinatal conditions; death, cause unknown; diseases of the genitourinary system; spinal osteoarthritis; diseases of the digestive systems nec; diseases of the skin and subcutaneous tissue, NEC; pneumoconiosis due to external agents.

workers who were working in manufacturing settings (data not shown). From 2001 to 2020, the number of robot-related claims in the manufacturing sector significantly decreased by 66.2%, from 68 claims in 2001 to 23 claims in 2020 ($p < 0.0001$), whereas robot-related claims in the services sector increased 33.3% from 6 in 2001 to 8 in 2020, although this increase was not statistically significant ($p = 0.505$) (data not shown).

TABLE 4 | Number and percentage of robot-related workers' compensation claims and total claim costs by claim severity and disability status, Ohio, 2001–2020.

Claim severity and disability status	Total claim count	Percent of total claims	Total claim cost	Percent of total claim costs	Mean cost	Median cost	Mean cost (non-zero claims)	Median cost (non-zero claims)
Medical-only (MO) claims	917	85.2	$748,452	9.0	$816	$446	$891	$485
Lost-time (LT) claims	159	14.8	$7,556,562	91.0	$47,526	$10,384	—	—
Temporary total disability (TTD)	70	6.5	$1,639,278	19.7	$23,418	$11,676	—	—
Permanent partial disability (PPD)	35	3.3	$280,245	3.4	$8,007	$5,073	—	—
Permanent partial and temporary total disability (PPTTD)	35	3.3	$1,321,680	15.9	$37,762	$20,294	—	—
Permanent total disability (PTD)	6	0.6	$4,066,419	49.0	$677,737	$651,118	—	—
Death Benefits	1	0.1	$154,863	1.9	$154,863	$154,863	—	—
Unknown	12	1.1	$94,077	1.1	$7,840	$2,786	—	—
Total	**1076**	**100**	**$8,305,014**	**100**	**$7718**	**$532**	**$8313**	**$570**

TABLE 5 | Number and percentage of robot-related workers' compensation claims and costs by event or exposure, Ohio, 2001–2020.

Injury event or exposure code (OIICS 1–digit codes)	Injury event or exposure description	Total claim count	Percent of total claims	Total claim cost	Percent of total claim costs	Mean cost	Median cost	Mean cost (non-zero claims)	Median cost (non-zero claims)
2	Transportation incidents	11	1.0	$47,419	0.6	$4311	$701	$4742	$1312
3	Fires and explosions	2	0.2	$906	< 0.01	$453	$453	$453	$453
4	Falls, slips, trips	114	10.6	$2,450,816	29.5	$21,498	$767	$23,341	$792
5	Exposure to harmful substances or environments	93	8.6	$72, 695	0.9	$782	$279	$887	$297
6	Contact with objects and equipment	623	57.9	$3,428,290	41.3	$5503	$508	$5942	$545
7	Overexertion and bodily reaction	222	20.6	$2,246,856	27.1	$10,121	$885	$10,598	$985
	All other (including unknown)	11	1.0	$58,032	0.7	$5276	$585	$5276	$585
	Total	**1076**	**100**	**$8,305,014**	**100**	**$7718**	**$532**	**$8313**	**$579**

TABLE 6 | Number and percentage of robot-related workers' compensation claims and claim costs by NORA sector, Ohio, 2001–2020.

NORA Sector	Total claim count	Percent of claims	Total cost of claims	Percent of total claim cost	Mean cost	Median cost	Mean cost (non-zero claims)	Median cost (non-zero claims)
Manufacturing	808	75.1	$5,478,612	66.0	$6780	$522	$7276	$570
Services	158	14.7	$882,454	10.6	$5585	$451	$6128	$517
Wholesale and retail trade	58	5.4	$230,582	2.8	$3976	$628	$4270	$687
Public safety	16	1.5	$117, 641	1.4	$7353	$1951	$7353	$1951
Construction	15	1.4	$1,287, 314	15.5	$85,821	$634	$91,951	$706
Healthcare and social assistance	12	1.1	$290, 102	3.5	$24,175	$4419	$29,010	$10,744
Agriculture, forestry, and fishing	5	0.5	$14,903	0.2	$2,981	$336	$726	$488
Transportation, warehousing, and utilities	4	0.4	$3406	< 0.1	$852	$873	$852	$873
Total	**1,076**	**100**	**$8,305,014**	**100**	**$7,718**	**$532**	**$8313**	**$579**

Abbreviation: NORA, National Occupational Research Agenda.

TABLE 7 | Number and percentage of robot-related workers' compensation claims by occupation, Ohio, 2001–2020.

Leading occupations (Top 10)[a,b]	Total claim count	Percent of total claims
51-4121-Welders, cutters, solderers, and brazers	123	11.4
53-7062-Laborers and freight, stock, and material movers, handlers	108	10.0
51-4199-Metal workers and plastic workers, all other	57	5.3
49-9041-Industrial machinery mechanics	56	5.2
51-9199-Production workers, all other	54	5.0
51-1011-First-line supervisors of production and operating workers	49	4.6
51-2099-Assemblers and fabricators, all other	46	4.3
51-4031-Cutting, punching, and press machine setters, operators, and tenders, metal and plastic	24	2.2
37-2011-Janitors and cleaners, except maids and housekeeping cleaners	22	2.0
51-9161-Computer numerically controlled tool operators	19	1.8
All other	284	26.4
Unknown	234	21.7
Total	**1076**	**100**

[a]Using the NIOSH Industry and Occupation Computerized Coding System (NIOCCS), 6-digit codes were assigned to text entry occupations based on the 2018 Standard Occupational Classification (SOC) system.
[b]These were based on total claim counts.

By claim costs, the top three sectors were manufacturing, construction, and services, which accounted for 66.0%, 15.5%, and 10.6% of total claim costs, respectively (Table 6). Notably, while construction contributed only 1.4% of all claims ($n = 15$), it accounted for over 15% of the total claim costs ($1.29 million), resulting in the highest average cost per claim at $85,821. Of these $1.29 million costs, 99% were due to falls, slips, trips ($n = 5$) (data not shown).

3.5 | Robot-Related Claims by Occupation

The top ten occupations with the highest claim count accounted for more than half of all robotics-related claims filed in Ohio during the period from 2001 to 2020 ($n = 558$, 51.8%) (Table 7). Welders, cutters, solderers, and brazers were the leading occupations ($n = 123$, 11.4%), followed by laborers, freight, stock, and material movers ($n = 108$, 10%) and metal and plastic workers ($n = 57$, 5.3%).

3.6 | Robot-Related Claims by Robot Type and Environment

An overwhelming majority of robot-related claims filed in Ohio during the period from 2001 to 2020 involved fixed-base robots ($n = 937$, 87.1%), in contrast to 5.9% of cases involving mobile robots (Table 8). The robot mobility type could not be determined for the remaining claims. Similarly, more than three-fourths of robot-related claims involved worker collaboration with robots ($n = 815$, 75.7%), while only 3.2% of injury claims involved autonomous or automatic robots ($n = 34$). The robot collaboration type could not be determined for the rest of the claims.

Contrary to robot feature identification, there was comparatively less information available to determine whether the robot involved was caged or powered at the time of the incident. Nearly 55% of the claims did not have enough information to determine whether the robot was caged or not ($n = 590$), 31.2% of claims involved uncaged robots ($n = 336$), and 13.9% of claims reported a caged robot being involved in the incident

TABLE 8 | Number and percentage of robot-related workers' compensation claims by robot type and environment, Ohio, 2001–2020.

Robot type	Total claim count	Percent of total claims
Robot mobility		
Fixed base	937	87.1
Mobile	64	5.9
Undetermined	75	7.0
Robot collaboration		
Collaborative	815	75.7
Autonomous/ Automatic	34	3.2
Undetermined	227	21.1
Robot environment		
Robot cage		
Caged	150	13.9
Uncaged	336	31.2
Undetermined	590	54.8
Robot power		
Powered	522	48.5
Unpowered	202	18.8
Undetermined	352	32.7
Total	**1076**	**100**

($n = 150$). Approximately, half of the claims involved a powered robot ($n = 522$, 48.5%) while 18.8% of claims involved an unpowered robot ($n = 202$). Robot power status could not be determined in nearly one-third of the claims filed ($n = 352$, 32.7%).

4 | Discussion

This study analyzed 20 years of robot-related injury claims in Ohio and presents findings on 1,076 claims. The manufacturing sector in Ohio reported the highest number of robot-related claims, both in claim count and total claim cost. Within this sector, the highest number of claims were reported in the motor vehicle manufacturing industries and the plastic and rubber manufacturing industries where the integration of robotics and automation technologies is increasingly prevalent. The leading occupations identified in this study, such as welders, cutters, solderers, brazers, metal and plastic workers, assemblers and fabricators, industry machine mechanics, and production workers, are predominantly employed within the manufacturing industries. This study also found that more than three-fourths of the reported claims involved worker collaboration with a robot. All these findings indicate that workers in highly automated settings may face additional injury risks associated with human-robot interaction. The industries identified in this study with a high number of claims were also identified in another study where robotic arms for collaborative applications were highly common [37, 38]. According to BLS employment statistics, Ohio and Michigan have two of the largest workforces in the motor vehicle and motor vehicle parts manufacturing industries in the United States [31]. These industries were the first to implement robots in the workplace, possibly reflecting why the manufacturing sector also has the highest robot-related injury and fatality counts in Ohio [5]

During this 20-year study period, overall robot-related claims significantly decreased, including in the manufacturing sector. This trend points towards multiple changes that have occurred in the robotics industry over the last two decades. ANSI and ISO published robotics safety standards and guidelines in 2006 and 2011 [18, 19]. These standards guided manufacturing industries to focus on improving robotics safety at the design and implementation phases in the workplaces. Furthermore, the decline in claim count over the two decades also corroborates with the introduction of new robotics safety standards for robotic arms for collaborative applications in 2012 and 2016, perhaps providing evidence of their effectiveness in reducing robot-related injuries. Additionally, advancements in robotics and technological developments over the past decade have likely contributed to improved safety in workplaces that involve robots.

In contrast to the trend observed in the manufacturing sector, claims in the service sector have risen over the 20-year period, and this trend warrants closer attention. Our study revealed that a significant number of claims from the temporary services industry involved workers employed in manufacturing settings, highlighting the risks temporary workers face when working with or around robots in manufacturing settings. Temporary workers often face unique challenges, including a lack of familiarity with the workplace and insufficient training on safety [39]. The Occupational Safety and Health Administration and NIOSH jointly developed recommended practices for protecting temporary workers, emphasizing the shared responsibility of both staffing agencies and host employers in ensuring the safety of temporary workers [39]. Several safety practices such evaluating worksites, training staff, defining safety responsibilities in contracts, conducting safety training, and maintaining communication were recommended to better protect temporary workers [39]. The rise in claims may also indicate the development of robots applicable to this services sector and their increasing adoption of robots across various industry groups within this sector. Currently, robot safety standards are primarily focused on the manufacturing industry. Given that the work environment, tasks, activities, risk exposures, and types of robots used in industry groups within the service sector may be different from the manufacturing sector, future efforts may be directed toward developing, defining, and documenting robot safety standards that address the industry groups in the service sector specifically.

This study reveals that there are significant differentials between the frequency of claims and their associated costs. While LT claims accounted for around 15% of all claims, they were responsible for a staggering 91% of total claims costs. Similarly, although falls, slips, and trips comprised only 10.6% of all claims, they contributed to 30% of total claim costs, with the average cost per claim almost three times the overall average cost per claim. Furthermore, the construction sector represented just 1.4% of total claims but accounted for over 15% of total claim costs, resulting in the highest average cost per claim ($85,821). These findings highlight the importance of evaluating these robot-related injuries and implementing a comprehensive, multi-faceted approach to mitigate and prevent robot-related injuries in the workplace. Robot safety in the workplace may be improved in five focus areas: robot design and safety controls [40]; robot safety standards and guidelines for design and implementation [19–22]; employee training [41]; workplace design or environmental factors [40, 42, 43]; and a robot-related injury reporting system [12]

To enhance HRI safety through robot design and controls, recent research by Cheng and colleagues [40] suggest implementing visual attention zones based on field of view, auditory attention zones corresponding to workplace noise levels, and avoidance zones for workers near mobile robots. These measures can help workers remain aware of potential hazards, as mobile robots could issue warning signals when approaching these zones to prevent collisions. Additionally, developing adaptive path planning strategies that respond to these warnings can further reduce injury risks in collaborative environments. The integration of artificial intelligence (AI) into robotics also holds promise for improving worker safety and productivity, particularly in sectors like architecture, engineering, and construction, by enabling applications such as clash prediction, hazard identification, and productivity analysis through computer vision techniques [38]. Another study established a framework for creating indoor maps and locating robots in manufacturing environments using computer vision techniques, defining contact avoidance zones around humans and obstacles. These zones allow robots to anticipate worker movements and plan safe paths, thereby reducing collision risks and injuries in collaborative work settings [42]

Establishing sector-specific or application-specific safety standards for robot design could allow guidelines to be tailored to the unique requirements of various tasks and work environments rather than relying on universal robot safety standards. This could be helpful for robot designers, manufacturers, and end users to have guidelines and standards that are more tailored to their requirements. The current study results on trends indicate that the developments in robot safety standards may have played a role in the decrease of robot-related injuries in the workplace over time. Standards like ISO 10218 [19–22], ISO/TS 15066 [44], ANSI/RIA R15.06 [15, 18], and ANSI/RIA R15.08 [16, 17] have established clear safety guidelines for traditional industrial robots, robotic arms for collaborative applications, and industrial mobile robots. These standards emphasize designing robots that are inherently safer, reducing the likelihood of injuries. Additionally, many workplace standards require a thorough risk assessment when implementing robots (e.g., ISO 12100 on risk assessment and risk reduction) [45]. Employers must evaluate potential hazards, implement safety measures, and continuously monitor the workplace for emerging risks. As robots become more prevalent in the workplace, it is crucial for robot safety standards to be regularly updated to keep pace with advancements in robotic technologies and systems.

Identifying worker groups such as temporary workers in the manufacturing settings who interact closely with robots, and providing them with focused training could help raise awareness about high-risk routine and non-routine tasks [39]. This training could inform the development of tailored safety protocols and standard operating procedures to address these risks. Workplace design and environmental factors also play a role in enhancing robotic safety [43]. Consistent with established safety standards (e.g., ISO 10218 on robotics safety requirements), considerations such as ambient noise levels must be evaluated to ensure that warning alerts from robots are audible above background sounds and noise levels [19, 20]. Additionally, in line with ISO/CIE 8995-1:2025 on lighting of indoor workplaces [46] attention to lighting conditions can help ensure that robot signals are clearly seen by workers and human detection capabilities are not compromised under poor lighting. Finally, when reporting robot-related injuries, it might be useful to include the model number of the robot involved [12]. This information could facilitate a more thorough analysis and understanding of incidents and robots involved, ultimately contributing to improved safety measures in the future [12].

NIOSH established the Center for Occupational Robotics Research (CORR) in 2017 to address the safety of workers who use, wear, or work with robots. CORR provides scientific leadership to guide the development and use of occupational robots that enhance worker safety. Examples of ongoing and past research efforts to reduce robot-related injuries include the development of "smart path" strategies for robot collision avoidance algorithms, examining force limits on human-robot contact events, investigating the effects of robot design on perceived safety and human behavior [47] evaluating effectiveness of robot-to-human communication modalities, and defining avoidance zones using path planning with mobile robots [40]. These research initiatives may further contribute to building evidence-based guidelines that enable safer integration of robotics into workplaces.

4.1 | Strengths and Limitations

To the authors' knowledge, this is the first study to describe robot-related WC claims and their costs, and it fills a significant research gap by providing detailed data on the frequency and nature of robot-related workplace injuries. The findings are subject to several limitations. First, the number of robot-related claims is an undercount of the true burden due to several factors: (1) OHBWC does not cover all workers, such as the self-employed, many contingent workers, and most very large employers, which tend to self-insure [32]; (2) although a systematic case-finding methodology was used to identify robot-related incidents, some potential cases may have been inadvertently missed due to the changing definition of robots and the robotics industry itself [34]; and (3) workers may not file a WC claim due to fear of retaliation, lost work time, or lack of understanding of the WC system [48, 49]. In addition, because reliable employee counts were not available for all employers, rates could not be calculated, limiting trend analyses over time to claim counts. Finally, the findings are specific to Ohio and may not be applicable to other states, as each state has different reporting and compensation rules that can affect the comparability of the data [32].

5 | Conclusions

Robotics is a rapidly evolving field driven by continuous technological advancements and increased adoption into the industrial, commercial, and domestic sectors. While emerging technologies help reduce risks associated with hazardous, repetitive, and physically demanding tasks, they can also introduce new workplace hazards. Keeping pace with these advancements can be challenging, but can be valuable to identify high-risk exposures, and implement a comprehensive, targeted, sector- or application-specific safety approach to ensure the safe implementation of robotics in the workplace.

Author Contributions

Vaishakhi Suresh designed the project, coded and analyzed the data, interpreted the data, and drafted the manuscript. Srinivas Konda analyzed and interpreted the data and assisted in data coding, project design and manuscript drafting. Justin M. Haney assisted with project design, data coding, data interpretation, and manuscript drafting. Hugo E. Camargo assisted with data coding and interpretation and reviewed the manuscript. Marvin Cheng assisted with data coding and interpretation and reviewed the manuscript. Darlene Weaver assisted with data coding and interpretation and reviewed the manuscript. Steven J. Wurzelbacher provided project administration support and assisted with data analysis, data interpretation, and manuscript review. Alysha R. Meyers provided project administration support and assisted with data analysis, data interpretation, and manuscript review. Steven J. Naber provided project administration and data acquisition support and reviewed the manuscript. Mike Lampl assisted with data acquisition and reviewed the manuscript.

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Disclosure

The findings and conclusions in this report are those of the authors and do not necessarily represent the official position of the National

Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC) or the Ohio Bureau of Workers' Compensation (OHBWC). Mention of any company or product does not constitute endorsement by NIOSH, CDC, or OHBWC.

Ethics Statement

This work was performed at the National Institute for Occupational Safety and Health and the Ohio Bureau of Workers' Compensation. This study was reviewed by Centers for Disease Control and Prevention (CDC), deemed not research involving human subjects, and was conducted consistent with applicable federal law and CDC policy (see, e.g., 45 C.F.R. part 46; 21 C.F.R. part 56; 42 U.S.C.§241(d), 5 U.S.C. §552a, 44 U.S.C. §3501 et seq.). No informed consent was required as the study analyzed existing de-identified workers' compensation claims.

Conflicts of Interest

The authors declare no conflicts of interest.

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Appendix A

TABLE A1 | Keyword search terms.

Keywords (search terms; inclusion criteria)	
Robot	(robot, bot, robto, robbot, cobot, manipulator, actuator, effector, encoder, servo motor, servomotor, teach pendant)
Autonom	(autonomous, autonomuos)
Mate	(automat)
Laser	(AMR, RGV, ROV, LIDAR, LGV, laser guide, AGV, automated guide, collision avoid, machine vision, remotely guide, obstacle detect)
Auto	(driverless, self drive, self-drive, selfdriv)
Exoskel	(exoskel)
Bionic	(Bionic, bionik)
Drone	(drone, unmanned aer, UAV, UAS, unmanned aircraft, remotely piloted)
Machine	(mechanical arm, lift arm, arm tool, armtool)