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Conceptual Design of an Industrial Manipulator for the Prevention of Musculoskeletal Disorders: A Participatory Approach

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Abstract

Background. This study outlines the conceptual design process of an innovative load manipulator adapted to the brewing industry, to mitigate ergonomic risk factors associated with manual handling of heavy loads, stacking, and manual palletizing.

Aim. To design a load manipulator for the function of "low-pressure table assistant" within a brewery.

Methods. A descriptive non-experimental study was accomplished, using an ergonomic and participatory approach, that is divided into three phases. Anthropometric adaptability and worker dimensions were assessed to determine the selected design. Finally, the given concept was thoroughly documented by creating drawings and technical data.

Results. The mean measured height was 173.4 centimeters, with a standard deviation of 4.6 centimeters, spanning a range of 165.8 centimeters (5th percentile) to 178.5 centimeters (95th percentile). This range suggests a moderate adequacy of the evaluated workforce in terms of height. Four main functions were identified: transporting boxes within the workspace, providing load support, allowing operator control, and ensuring safety. In addition, with this lifting device, the operator can handle 2, 4, or even 6 boxes simultaneously, with speed, flexibility, and functionality.

Conclusions. In particular, the developed concept introduces significant innovations, such as the ability to, simultaneously handle several heavy loads and the integration of double-jointed pivots, which extends its operational range. These innovations contribute to the prevention of forced postures and manual lifting of heavy loads.

Keywords: ergonomics, equipment design, industrial manipulator, prevention, musculoskeletal disorders

1. INTRODUCTION

Tasks involving manual handling of loads (MHL) can expose workers to various risk factors, primarily of a physical nature (Castillo-Gonzalez, 2022; Lobato et al., 2023). When these tasks are performed repeatedly or over extended periods, they may lead to overexertion and injuries (Acosta, 2022) The primary risk factors associated with musculoskeletal disorders (MSD) resulting from MHL include uncomfortable postures (such as torso flexion and twisting, deviating from ergonomic angles), repetitive movements, and prolonged static positions (Cubillos, 2023; Ron et al., 2023a; Rossi et al., 2013; Zea Quispe et al., 2022).

According to the Overexertion Injuries Report from Spain in 2020, 47% of injuries related to overexertion were attributed to activities associated with MHL, with approximately 30,6% occurring in the back segment. The food industry emerged as the most affected sector, accounting for 3,5% of these cases (Niazoa et al., 2022; Ron et al., 2023b). Additionally, the Sixth European Survey of Working Conditions conducted in 2015 revealed that roughly 37% of all workers are exposed, to the risk of lifting or moving heavy loads for at least a quarter of their working hours. (Instituto Nacional de Seguridad e Higiene en el Trabajo (INSHT), 2021) MHL represents the primary cause of health-related issues in the American workforce, with approximately 50% of reported backaches attributed to lifting, 10% to pulling and pushing, and about 6% to handling of loads (Instituto Nacional de Seguridad e Higiene en el Trabajo (INSHT), 2017). Similar results were found in other scenarios (Ron & Escalona, 2023; Ruiz et al., 2022).

In Venezuela, statistics from the National Institute of Health and Work Safety (INPSASEL, 2006) reveal that musculoskeletal disorders (MSD) constitute the highest percentage of reported illnesses, standing at 76,4%. Within this category, back injuries comprise approximately 67.5%, representing a significant health concern in the manufacturing industry and ranking first in the registry of occupational illnesses at 56,33% (Dormohammadi et al., 2012; Ramírez et al., 2023).

In response to the risks posed by MHL to the safety and health of workers, Venezuela introduced the Technical Standard for the Control of Manual Handling, Lifting, and Transfer of Loads (NT-04-2016) in 2016. Article 3 of this standard defines manual handling of loads as "any operation that necessitates the use of human force to lift, lower, push, pull, transport, or execute any other action for moving or stopping an object, person, or animal". Additionally, loads are defined, as "any object, person, animal, or item requiring manipulation, lifting, or movement, with a weight equal to or greater than 3 kilograms" (Dormohammadi et al., 2012).

Technical Standard implies that, within workplaces, manual handling of loads outside the recommended zone should be minimized, as much as possible. Otherwise, the application of technical assistance methods must be employed, as a risk mitigation measure (Gómez Cano et al., 2023). Article 18, of this standard explicitly states: that employers, cooperatives, and other community-based production or service entities are obligated to ensure the implementation of mechanical and/or administrative technical assistance means based on recommendations derived from ergonomic studies. These means must be tailored to the identified conditions, align with workers' anthropometric characteristics, and align with the organization and division of labor.

To mitigate musculoskeletal disorders associated with high-risk manual handling tasks, material handling devices have been developed globally to eliminate or reduce the risks associated with lifting. This equipment facilitates a range of tasks, including assembly, racking, and palletizing, as well as the vertical and horizontal transfer of loads (Dávila-Morán et al., 2023). Material handling devices are categorized into two main groups: simple mechanical assistance (comprising supports, basic carts, hook systems, bars, levers, and trolleys) and complex mechanical assistance (encompassing conveyor equipment, cranes/elevators, forklifts, and industrial manipulators) (Dávila-Morán et al., 2023).

Industrial manipulators fall under the category of complex mechanical assistance. According to the European Standardization Committee, an industrial manipulator is defined as "a motorized machine in which the operator must be in contact with the load retention device to guide and/or control the movement of the load to a specified position in the workspace" (Regalado García et al., 2023). The fundamental purpose is straightforward: to reduce the static (gravitational) load that the workers must handle, thus expecting a decrease in musculoskeletal stress.

Given that these industrial manipulators are destined to provide direct assistance to workers in material handling tasks, participatory ergonomics emerges as a recommended approach since it engages users right from the initial stages of development. Using methods such as interviews, active observation, and workgroups, contextualized requirements that enhance the interaction between individuals and manipulator systems can be identified (Labrador Parra et al., 2023). The experience and knowledge of operators are integral elements in the ergonomic and effective design of this equipment, with the primary goal of reducing physical load and preventing musculoskeletal disorders (Instituto Nacional de Prevención, Salud y Seguridad Laborales (INPSASEL), 2016).

Through approaches like focus groups, interviews, participant observation, and joint activity analysis with the workers, precise ergonomic demands and requirements can be pinpointed. These findings are subsequently translated collaboratively into technical specifications for the manipulator (Ministerio del Trabajo y Previsión Social, 2018). The composition of workgroups with diverse profiles, including technical experts and operators, fosters creativity, amalgamates various sources of knowledge, and establishes consensus for an optimal and adaptable design.

Considering the above, this current study is part of a broader investigation conducted by Ron, Escalona, and Cáceres (Ron et al., 2018). In this research, an ergonomic assessment of the "low-pressure table assistant" role within a brewery was conducted, revealing the presence of risk factors for musculoskeletal disorders associated with the manual palletizing of 11 kg of beer. In light of this, the objective outlined in this study is to design an industrial manipulator for the "low-pressure table assistant" position in a brewery. To achieve this goal, the study first identified the design requirements of the equipment. Subsequently, it specified the design criteria for the manipulator and, finally, developed the conceptual design of the industrial manipulator, tailored to the anthropometric characteristics of the workers and ergonomic design principles (Briede Westermeyer, 2010; Pérez Lorca, 2019).

2. METHODS

This investigation is situated within a non-experimental design framework with a descriptive level, adopting an ergonomic and participatory approach. It involved active participation from the workers in the area, supervisors, engineers, doctors, occupational health and safety personnel, and management (Cardoza et al., 2023; Inastrilla, 2023).

As such, it was a user-centered investigation developed in three phases, which are outlined below:

During **phase 1**, the necessities for the development of the industrial manipulator were identified.

To achieve this goal, we initiated by specifying production demands and user needs through functional analysis (European Standard, 2010). This method is based on an understanding of the fundamental operating principles that the product must adhere to while discerning the essential components needed to fulfill its global function. From this global function, each subfunction is identified as a breakdown of the previous one. During the execution process, we addressed the question: "What should the subsystem do to fulfill the function?" always taking into consideration the flow of materials, energy, or information. This analysis was visually represented by a functional diagram. The techniques and instruments employed included observation, unstructured reviews, and a review of previous research conducted by Ron, Escalona & Cáceres (Ron et al., 2018).

Subsequently, anthropometric measurements of the workers were obtained. Each worker's height (in centimeters) was measured in a standing position while wearing safety clothing and footwear to ensure the relevance and quality of the data collected. Other anthropometric variables were estimated using the proportionality constants of the standing human body proposed by Drillis and Contini in 1966 (Hignett et al., 2005). The study encompassed the measurement of the following anthropometric variables: height (H), shoulder-to-floor height (SFs), elbow-to-floor height (EFs), wrist-to-floor height (WFs), shoulder-wrist distance (SW), and elbow-wrist distance (EW). Height measurements were taken using a conventional tape measure, and the estimated data were recorded in an Excel® database for the subsequent generation of descriptive statistics, including mean, standard deviation, 5th percentile, and 95th percentile (Contini et al., 1963).

Phase 2 involved the definition of functional, ergonomic, technological, and formal design requirements. For this purpose, participatory ergonomics was employed, constituting a multidisciplinary team comprising eight individuals, one of whom was the author of this study (Vink et al., 2008). The team consisted of an occupational health specialist, an engineering manager, a packaging manager, a purchasing analyst, a quality control manager, an area supervisor, and two of the most experienced workers. All design requirements were collaboratively identified by the project team.

Finally, in **Phase 3**, the development of the conceptual design of the industrial manipulator was developed by integrating the previously identified requirements and necessities. Initially, design alternatives were generated through sketches and models, exploring various configurations that align with functional, anthropometric, and load capacity specifications (Broberg & Hermund, 2004). These alternatives underwent collective evaluation, leading to the selection of the concept that best met the ergonomic and usability requirements (Sánchez Zambrano & Mayorga Torres, 2016; Silva-Sánchez, 2023).

The chosen design was further developed by validating dimensions and anthropometric adaptability. Ultimately, the resulting concept was comprehensively documented, incorporating technical specifications and plans. This methodology ensures an optimal design tailored to the specific context, fully aligned with the previously established necessities and requirements.

3. RESULTS AND DISCUSSION

Table 1. **Anthropometric measurements of the workers with the job position as "low-pressure table assistant" (n=10)**

Measurements (cm)	X	DS	Percentile	
			P5	P95
Height (H)	173,4	4,6	165,8	178,5
Shoulders-Floor Height, standing (SFs)	141,8	3,8	135,6	146,0
Elbow-Floor Height, standing (EFs)	109,2	2,9	104,4	112,5
Wrist-Floor Height, standing (WFs)	84,1	2,2	80,4	86,6
Shoulder-Wrist Distance (SW)	57,5	1,5	55,0	59,3
Elbow-Wrist Distance (EW)	25,3	0,6	24,2	26,0

Adapted according to Compiled from height measurements of the workers, applying the proportionality factor by Drillis y Contini (2018).

Table 1 presents the descriptive statistics of anthropometric variables, both measured and estimated, for the workers holding the job position of "low-pressure table assistant". It may be observed that the mean height stood at 173,4 cm, accompanied by a standard deviation of 4,6 cm. The height range spans from 165,8 cm (5^{th} percentile) to 178,5 cm (95^{th} percentile), signifying a moderate variance within the height measurements of the assessed workforce. The measurements of body segment lengths, including the shoulder, elbow, and wrist, reveal narrow percentile ranges, indicating a high degree of homogeneity in anthropometric characteristics within the sample. These percentile data will facilitate the establishment of critical dimensions for the industrial manipulator design at an average size and encompassing the extremes.

Table 2 systematically delineates the decomposition of the load-handling process into global and specific functions, following the functional analysis methodology. Four main functions are discerned: the transportation of boxes within the workspace, the provision of load support, enabling operator control, and ensuring safety. Every one of these global functions is broken down into several elementary subfunctions, that are needed for its execution.

Table 2. **Design necessities of the industrial manipulator**

Global Function	**Subfunction**
The transportation of boxes within the workspace	To grab a box To elevate the box To transport the box horizontally To position the box in a proper place. To drop the box
To provide load support	To ensure structural integrity To bear static loads To bear dynamic loads To distribute the load onto supports
To enable the operator to control	om ove vertically om ove horizontally To orient To initiate grip To provide feedback
To ensure safety in the operation	Load stabilization. Precise velocity control Overload detection mechanisms Emergency stop functionality Ergonomic-designed controls Easy to learn how to operate it A proper adaptation to the user's body dimensions To minimize uncomfortable or forced postures.

According to Research data (2023).

The systematic identification of design requirements was facilitated by the preceding functional analysis, as the subfunctions could be turned into technical characteristics and specifications of the equipment. For instance, the subfunction "to provide load support" transforms into the requirement "a load capacity of 11 kg during idle periods". The table comprehensively delineates the array of functions that the industrial manipulator must execute. This analysis is fundamental during the initial phases of design, enabling an in-depth comprehension of the product's purpose and usage context.

Table 3. **Design requirements of the industrial manipulator**

Funcional requirements	**Ergonomic requirements**	**Technological requirements**	**Formal requirements**
Minimum load capacity of 11 kg	Rotary control knobs for intuitive operation	Stainless steel structure with a thickness of 1.5mm.	Polished surfaces and rounded edges
Maximum lifting height of 1,47 m (95th percentile for shoulder height)	Control placement between 25° a 40° below the plane and at a height of 25 cm	Components in ABS or PVC with a thickness of 5 mm	Compact design

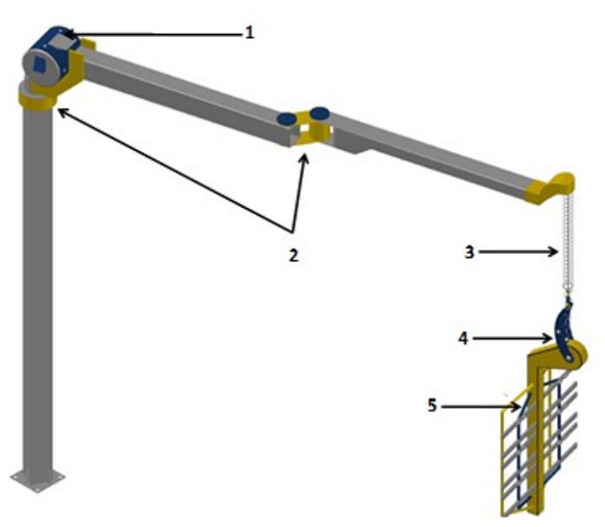
Funcional requirements	**Ergonomic requirements**	**Technological requirements**	**Formal requirements**
Minimum lifting height of 1,10 m (5th percentile for Elbow-Floor Height)	Control diameters between 20 y 40 mm (5th and 95th Percentiles)	Electric Actuators with 30 kg capacity and a 60 cm stroke	Yellow paint on moving parts and grey on structures.
Forward and lateral horizonal reach of 60 cm	Separation of controls by 50 mm	12V 5Ah lithium-ion battery with 2 hours of battery life	Identification with engraved pictograms > 5mm
Lifting velocity from 0 to 15 cm/s with variable control	Sound alerts <65 dB	250W 24V DC travel motor with a 1:50 reducer	Rubber protections in edges and corners.
Maximum travelling velocity of 1 m/s	Force controls < 3 kg	Control circuit with protection	
Gripping and clamping box systems	Operation in neutral posture		
Steering systems	Appropriate visibility of the load and the environment.		

According to Research data (2023).

Having defined the design necessities, the process of developing design requirements commenced. Accurate specification of design requirements constitutes a pivotal phase in the development of any product. This is because it establishes the features and capabilities that the system must fulfill in an organized and explicit manner to satisfy the identified necessities.

Table 3 presents an exhaustive compilation of the design requirements for the industrial manipulator, categorized into functional, ergonomic, technological, and formal specifications. It provides a comprehensive description of critical aspects such as load capacity, ranges of movement, control types and locations, material selection, and finishing details, among other essential specifications required for achieving an ergonomic design and the practical construction of the industrial manipulator. The meticulous documentation of these detailed and well-informed requirements serves as a robust guide for developing an optimal concept that is finely adapted to its usage context and user characteristics. This approach ensures the creation of equipment that can effectively reduce physical exertion and mitigate musculoskeletal injuries associated with the manual handling of heavy loads.

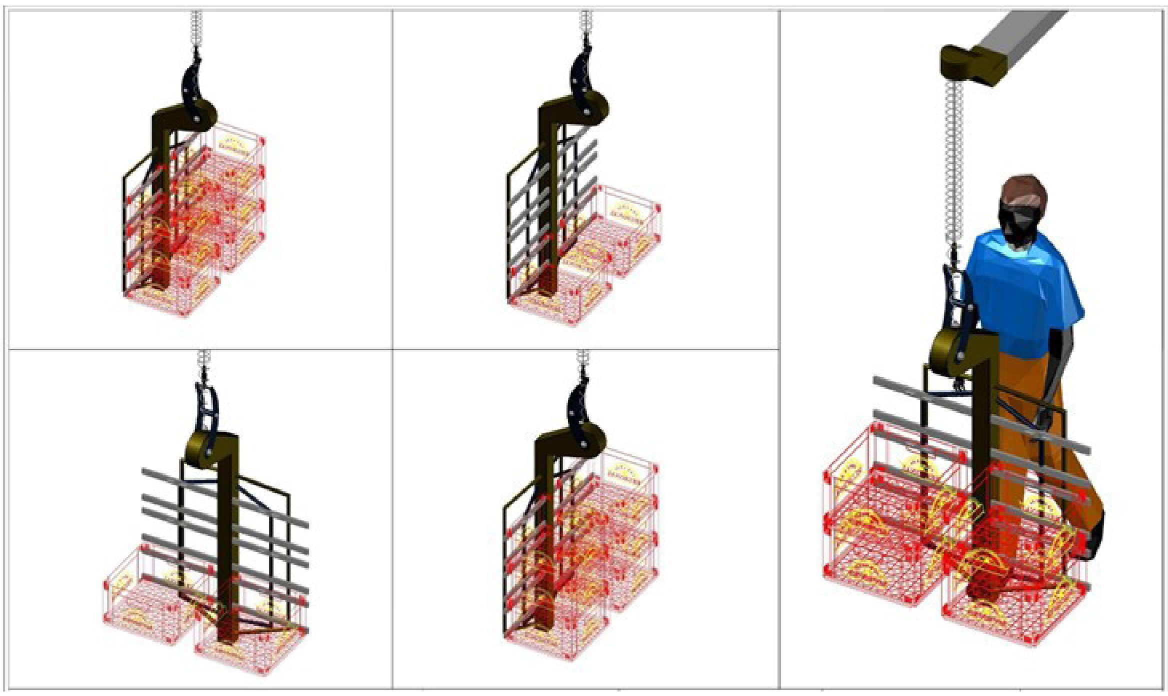
Figure 1. **Conceptual design of the industrial manipulator**

Selected design	Feature
	**1. Pneumatic balancer:** operates entirely pneumatically, facilitating elastic movement both upwards and downwards. **2. Pivots:** utilize a double pivot structure to expand the sphere of action. **3. Armored control cable:** features a multi-core design. **4. Center of gravity unit:** ensures vertical alignment in all manipulator positions, whether it is empty or loaded, with an automatic reaction or activation of capabilities. **5. Ergonomic handle:** enables vertical movement and activation of key additional functions.

According to Research data (2023)

The lifting device shown in the above figure permits the operator to manipulate 2, 4, or 6 boxes per manipulator operation. This versatile equipment facilitates rapid, flexible, and highly functional processes; with this device, the worker can perform tasks such as packing, stacking, and palletizing at various heights, according to the characteristics of the tasks and the individual needs of the worker (Labrador Parra et al., 2023).

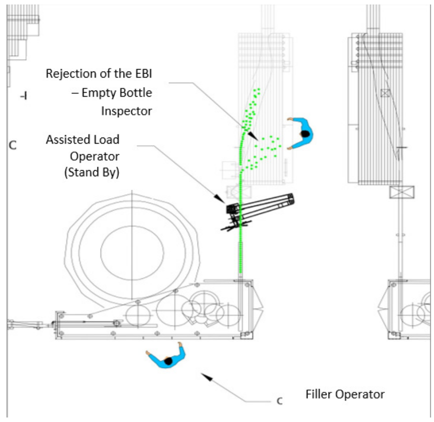
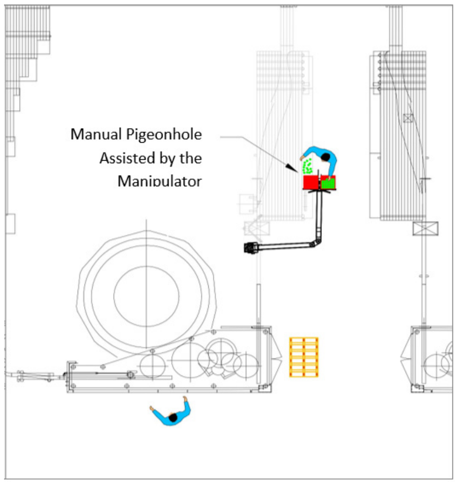
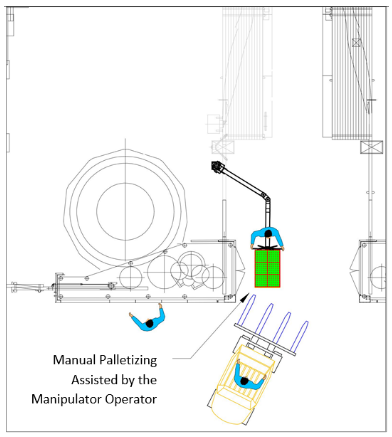
Figure 2. **Simulation of box stacking**



According to Research data (2023)

In Figure 2, the simulation of box stacking is observed, showing the capacity to manipulate multiple loads at the same time and how the articulated double pivots substantially enlarge the sphere of action compared with conventional manipulators.

Table 4. **Use of the industrial manipulator at the workspace**

Task	Figure
Rejection of bottles. Initially, the operator takes the bottles that are rejected by the inspector as full bottles. The rejection of these bottles could be because they have a low content of liquid or simply because of an equipment failure. The operator collects these bottles and discharges any liquid contained into the canal of the rejection table.	
Manual Pigeonhole Operation. Following the rejection process, the operator has the possibility of leaning on the equipment at the beginning of the task. This system offers the possibility of placing the equipment in front of the worker to feed it with empty pigeonholes; once they are located in the equipment, the worker fills the pigeonholes manually, avoiding physical exertion.	
Palletizing using the Industrial Manipulator. In this final phase, the operator manages the equipment, which is already loaded with 2, 4, or 6 boxes. The operator then transfers these boxes to the palletizing area or temporary storage location, thereby eliminating the need for manual packing, stacking, and palletizing of the boxes.	

According to Research data (2023)

Table 4 shows the various tasks performed by individuals in the “low-pressure table assistant” job position. These tasks include bottle rejection, manual pigeonhole handling, and ultimately, the palletizing process employing the designed Industrial Manipulator. The figure illustrates how activities such as manual packing, pushing, and manual palletizing are eliminated.

4. CONCLUSIONS

This study describes the conceptual design process of an innovative industrial manipulator aimed specifically at the brewing industry, seeking to reduce the non-ergonomic risk factors associated with manual handling of loads (heavy boxes), packing, and manual palletizing. Regarding the developed concept, it introduces important innovations such as the ability to manipulate multiple boxes at the same time and the double pivot structure that substantially enlarges the operational sphere of action compared to conventional manipulators. This contributes to the prevention of forced postures and the manual handling of hefty loads.

The predominant limitation of this study lies in the absence of quantitative measurements to validate the anticipated reduction in physical stress relative to traditional manual handling techniques. Considering this, it is advisable to complement the research with biomechanical tests and subjective perception evaluations conducted within authentic usage scenarios.

In sum, the methodology and findings of this study demonstrate congruence with prior research in the field of user-centered industrial manipulator designs. Important innovations in terms of versatility and anthropometric adaptability are presented in the developed concept. Nonetheless, the concretization of the conceptual design and its subsequent quantitative analysis within real-world contexts is imperative to validate the expected advantages.

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Declaration of Authorship:
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Data curation: Misael Ron, Evelin Escalona, Estela Hernández-Runque, Javier Gonzalez-Argote.
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Pramoninio manipuliatoriaus, skirto raumenų ir kaulų sistemos sutrikimų prevencijai, koncepcinis projektas: dalyvaujamasis metodas

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Santrauka

*Tyrimo pagrindimas***.** Tyrime aprašomas inovatyvaus krovinių manipuliatoriaus, pritaikyto alaus pramonei, koncepcinis projektavimo procesas, siekiant sumažinti ergonominius rizikos veiksnius, susijusius su sunkių krovinių tvarkymu rankomis, krovimu į krūvas ir padėklų krovimu rankomis.

Tikslas. Suprojektuoti krovinių manipuliatorių, skirtą atlikti „žemo slėgio stalo asistento" vaidmenį alaus darykloje.

Metodai. Atliktas aprašomasis neeksperimentinis tyrimas, taikant ergonominį ir dalyvaujamąjį metodą, sudarytą iš trijų etapų. Siekiant sukurti pasirinktą dizainą, įvertintas antropometrinis pritaikomumas ir darbuotojo matmenys. Galiausiai pateikta koncepcija kruopščiai dokumentuojama, parengiant brėžinius ir techninius duomenis**.**

Rezultatai. Vidutinis išmatuotas ūgis – 173,4 cm, standartinis nuokrypis – 4,6 cm, apimantis diapazoną nuo 165,8 cm (5-asis procentilis) iki 178,5 cm (95-asis procentilis). Šis intervalas rodo, kad tirtų darbuotojų ūgis yra vidutiniškai tinkamas. Nustatytos keturios pagrindinės funkcijos: dėžių transportavimas darbo erdvėje, krovinio laikymas, operatoriaus kontrolė ir saugos užtikrinimas. Be to, naudodamas šį kėlimo įrenginį, operatorius vienu metu gali dirbti su dviem, keturiomis arba net šešiomis dėžėmis, o tai užtikrina greitį, lankstumą ir funkcionalumą.

Išvados. Visų pirma, pagal sukurtą koncepciją įdiegtos svarbios naujovės, pavyzdžiui, galimybė vienu metu kelti kelis sunkius krovinius, dvigubo šarnyro integravimas, kuris išplečia veikimo diapazoną. Šios naujovės padeda išvengti nepatogių pozicijų ir sunkių krovinių kėlimo rankomis.

Reikšminiai žodžiai: ergonomika, įrangos dizainas, pramoninis manipuliatorius, prevencija, raumenų ir kaulų sistemos sutrikimai

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