



Original Article

New ergonomic device to improve occupational safety of blasthole drill operators



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ABSTRACT

The relationship between mining companies and the society is not limited to the local communities surrounding the operations. The evaluation of the working conditions of the operators of mining equipment is an important dimension of the relationship with the society. Even with the increasing level of automation, there are equipment and operating procedures that have to be adjusted to meet the employees' capabilities and requirements. For instance, the bit replacement activity requires significant physical work from the employees involved in rock drilling operations. This means that modifications are required in blasthole drills to address the employee's accessibility to bit holders and toolboxes in the drilling platform. However, only a limited number of recent studies have considered ergonomic issues for mining equipments. This research proposes a new ergonomic device for blasthole drills to reduce the ergonomic risk of the operators without affecting the performance. The methods include simulation tools and ergonomic analysis based on the NIOSH Lifting Equation (NLE). The results of the application of the new ergonomic device in all bit replacement tasks have shown risk indexes below the critical limits established by NIOSH. The results have also indicated a performance improvement, with a 60% reduction in bit replacement time.

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1. Introduction

The majority of large-scale mining units require use of intensive labor. Regarding open pit mining operations, the largest share of the workforce is concentrated in mining operations and mineral processing [1]. Operations of world class

mineral deposits also have a high degree of mechanization and automation in both stages. However, there are some operations that still require significant physical effort from employees in some tasks, e.g. drilling and blasting operations which will be addressed in the present work. Exploitation of metallic minerals often requires drilling and blasting operations due to the hardness of minerals and rocks [2]. This

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configuration ensures that these industrial units reach a high-scale production with competitive costs. Additionally, the exposure of some employees to activities with excessive physical effort and ergonomic risks may affect economic and social aspects.

In recent decades, the mining industry has been widely questioned by society about its practices. Working conditions to which employees are subjected are one of the ways the mining industry engages with communities. The analysis and solutions for health and safety risks are dimensions that 21st century mining needs new practices. Aspects related to fuel consumption, tire wear management and greenhouse gas emissions already have practical examples updated with the 21st century mining industry standards [3,4]. Some authors emphasize the need for compatibility among mining equipment as the key factor to achieve energy efficiency, productivity and safe operations [5,6]. Besides the compatibility, the definition of mining pit geometry also allows reaching greater operational efficiency of the equipment [7]. The need of synergy among different entities inserted in a productive process is a common understanding in recent literature about health and safety conditions, sustainability and operational efficiency.

When considering manual or mechanical replacement procedures applied to rock drilling accessories, a comparative analysis is required. There are still no recent examples of blasthole drill customizations in order to eliminate ergonomic risks. The exposure of blasthole drill operators to excessive physical effort is still a usual practice in small or major mining companies. Other industrial sectors, such as electronics, aerospace and automotive, have developed several methods of ergonomic risk analysis in the last decades. The present research used specific methods to measure the risk of activities involving manual lifting of objects. These analysis tools have been adapted to mining. It is an innovative approach that seeks to answer an important question. How can the ergonomic risks of rock drilling bit replacement tasks be eliminated without efficiency loss or new risks to operations?

The aim of the research reported here was to develop a mechanical device for bit replacement tasks to reduce the ergonomic risks of manual procedures. Ergonomic assessments support the comparative analysis between mechanical and manual procedures. The blasthole drill adjustments for the ergonomic device were developed based on employees' biomechanical characteristics. In addition to eliminating the need for lifting loads, there was an evaluation of the operational efficiency of the mechanical device. The NIOSH Lifting Equation (NLE) is the main concept applied in the ergonomic analysis developed in the present work. The results support the definition of compatibility parameters between the equipment and employees. Therefore, this device can ensure a better working condition without efficiency loss. The mechanical device was developed and installed in a blasthole drill of a large iron mine in Brazil. The studied mine needs drilling and blasting operations to remove around 40% of total exploitation. Regarding the drilling operations, the fleet is composed of five equipment vehicles.

Several recent studies seek to adjust equipment and operations to reduce greenhouse gas emissions [8-10]. It is also possible to mention some studies that seek greater

operational efficiency and safety in new blasthole drill designs [11]. However, straightforward analysis regarding process mapping applied to ergonomics is not yet a practice in mining. The present work has great relevance to demonstrate the feasibility of equipment customization aiming to improve ergonomic conditions. This practice is not restricted only to a simulated environment, but it concerns large mining companies, professionals and society. The association between scientific research and mineral industry procedures is the key to a better relationship with society in the 21st century.

2. Methodology

Most surface mining operations of large companies have a high degree of mechanization and automation. However, some steps of the production process require manual activities involving ergonomic risks to operators. There are specific tools that can measure the criticality level of ergonomic risks in each task. Considering mining operations, the ergonomic risks are concentrated on drilling and blasting operations that require manual lifting tasks. Hence, the present study uses a prioritization matrix to identify which task presents the greatest potential for ergonomic risk. The matrix parameters must be compatible with the research objectives. According to the matrix results, bit replacement is the activity that presents the greatest potential of ergonomic risks. The prioritization assessment will be detailed below.

After defining the scope of analysis, the detailed analysis of the bit replacement activities was started. The first analysis tool is the ergonomic process map that measures the operators' physical effort as a function of the running time for each bit replacement task. The second step is to evaluate each task with the NLE that measures the level of ergonomic risk. The present research seeks to develop a solution able to avoid the need for excessive physical effort according to the criticality of lifting tasks. After evaluation, blasthole drill customization with an articulated device for bit replacement was pointed out as a possible solution to reducing ergonomic risks. Based on the analysis of the results obtained after the device installation, the ergonomic risk level is verified once more. This analysis includes process mapping and ergonomic risk assessment using NLE for the new bit replacement procedure.

In addition to aspects related to ergonomic risk, the rock drilling efficiency will be evaluated after equipment customizations. It is very important that health and safety risks are avoided without reducing the efficiency and productivity of industrial processes. Specific solutions addressed to operational safety can also achieve operational effectiveness when they do not affect the economic viability [12]. All the technical evaluation of bit replacement was carried out in an iron mine located in the south-eastern region of Brazil.

2.1. Quality assessment tools applied to drilling and blasting operations

The use of some quality assessment tools of industrial processes is necessary to achieve the objective established in the present research. The tools were applied in the prioritization,

Table 1 – Matrix for prioritization related to ergonomic risk, operational costs and operational efficiency.

Parameters of analysis	Rating	Operational tasks			
		Blasting operations	Bit replacement	Hammer replacement	Equipment relocation
Ergonomic risk	1 – Low risk				
	3 – Substantial risk	×		×	×
	5 – High risk		×		
Operational costs	1 – Low impact				
	3 – Intermediate impact	×	×		×
	5 – High impact			×	
Productivity/efficiency	1 – Efficiency loss	×		×	×
	3 – No efficiency loss				
	5 – Productivity/efficiency increase		×		
Total	7	13	9	7	

analysis and process mapping following fundamental principles of the Deming Cycle. Therefore, the attendance of drilling and blasting staff is a basic premise for this research. There were 24 drilling operators and 36 rock blasting employees involved in the present assessment. These professionals cover the total drilling and blasting headcount of the studied mine. There were interviews, mine visits and equipment inspections to set out which operational tasks have the greatest risks to operators' safety. Table 1 presents the four operational tasks pointed out by the staff which were analyzed by a prioritization matrix. The parameters of the prioritization matrix are: degree of ergonomic risk, impact on operating costs and impact on productivity/efficiency of drilling and blasting processes. Each task assigns a score for each parameter in the matrix according to specific operational analysis. The score assignments count on the participation of each employee during the execution of their tasks. The prioritization matrix identifies the most critical operational task by scoring the final results. In this case, the bit replacement was identified as the most critical task. Therefore, this activity will be the subject

of the next stages of analysis and technical solution development aimed at reduction of ergonomic risk.

Activities related to drilling accessory replacement have a high criticality due to the need of manually lifting and carrying the accessories. Hence, the bit replacement will be mapped by relating the intensity of physical effort and exposure time of each task. Since employees make efforts above the 23-kg limit, there is great potential for developing injuries [13,14]. Fig. 1 shows the process map detailing each step of the bit replacement. Table 2 shows the description of each step of the process map, according to the sequence of letters available in Fig. 1. As indicated in the figure, the lifting steps represent the critical points. The criticality of each step is greater depending on the load (weight) or duration time.

Considering Fig. 1 and Table 2, tasks A, C, F and H have a high level of criticality during the bit replacement. These tasks require the handling of bits and chain wrenches that have weight above the 23-kg limit. Besides the load, it is necessary to measure the duration of each task, the frequency of repetitions and other specificities of this activity. Furthermore,

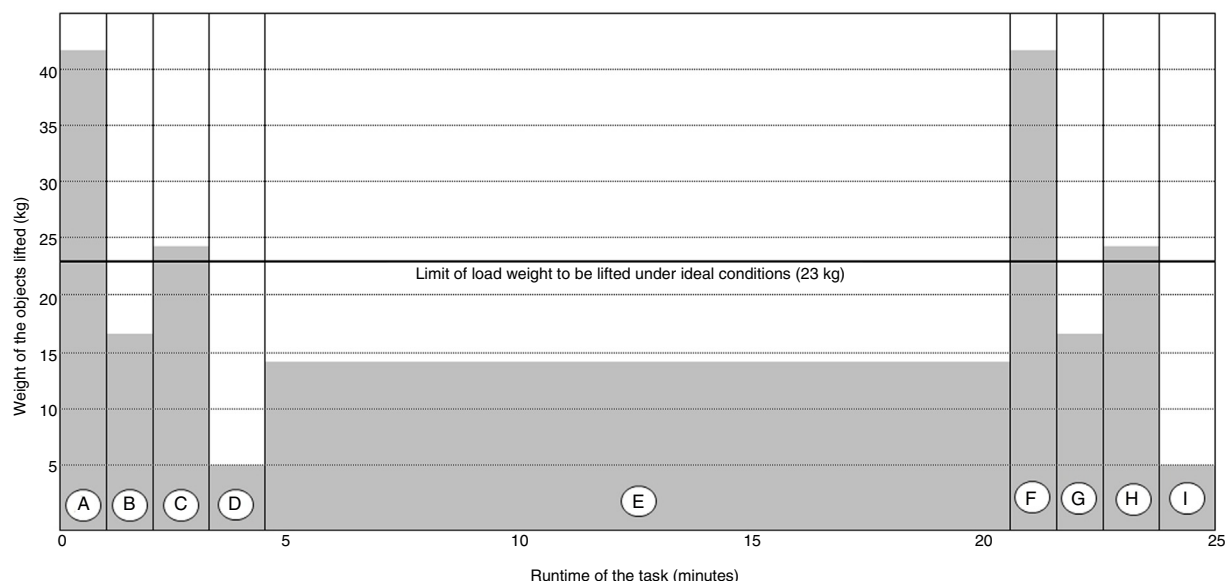
**Fig. 1 – Process map of bit replacement tasks indicated by letters.**

Table 2 – Complete task description of a bit replacement and lifted tool weight.

Task	Description	Lifted tools and weight
A	Lifting new (or restored) bit from bit holder to blasthole drill platform	Drill bit (42 kg)
B	Lifting coupling lock from equipment toolbox to blasthole drill platform	Coupling lock (17 kg)
C	Lifting chain wrench from equipment toolbox to blasthole drill platform	Chain wrench (24 kg)
D	Lifting level support from equipment toolbox to blasthole drill platform	Level support (5 kg)
E	Bit replacement	Handling tools, accessories and devices (13 kg)
F	Lifting worn bit from blasthole drill platform to bit holder	Worn bit (42 kg)
G	Lifting coupling lock from blasthole drill platform to equipment toolbox	Coupling lock (17 kg)
H	Lift chain wrench from blasthole drill platform to equipment toolbox	Chain wrench (24 kg)
I	Lift level support from blasthole drill platform to equipment toolbox	Level support (5 kg)

Table 3 – Conversions from task parameters to multipliers.

Task parameters	Definition and units	Multiplier equations
LC (Load Constant)	Maximum recommended load weight to be lifted under ideal conditions (kg)	LC = 23 kg
HP (Horizontal Parameter)	Horizontal location of the object relative to the body (m)	Horizontal Multiplier $HM = 25/HP$
VP (Vertical Parameter)	Vertical location of the object relative to the floor (m)	Vertical Multiplier $VM = 1 - (0.003 \times VP - 0.75)$
DP (Distance Parameter)	Distance the object is moved vertically (m)	Distance Multiplier $DM = 0.82 + (4.5/DP)$
AP (Asymmetry Parameter)	Asymmetry angle or twisting requirement (°)	Asymmetry Multiplier $AM = 1 - (0.0032 \times AP)$
FP (Frequency Parameter)	Frequency and duration of lifting activity (lifts/minute). All bit replacement tasks have $FP \leq 1$ lift/minute	According Waters et al. [14], the value of Frequency Multiplier (FM) is 1 ($FM = 1$) for $FP \leq 1$ lifts/minute
CP (Coupling Parameter)	Coupling or quality of the worker's grip on the object. CP = 1 (Good), CP = 2 (Fair) and CP = 3 (Poor)	According Waters et al. [14], the value of Coupling Multiplier (CM) is: <ul style="list-style-type: none"> • CM = 1 if CP = 1 or CP = 2 and $VP \geq 75$ cm • CM = 0.95 if CP = 2 and $VP \leq 75$ cm • CM = 0.9 if CP = 3

it is important to note that the lifting of these tools and accessories happens in an active open pit mine. Operators lift and carry these objects for up to 20 m on an uneven ground. All this information and variables are components of an ergonomic analysis. These data guided the present work in the development of blasthole drill customization. Torma-Krajewski et al. [15] claim that new work tools generate significant modifications in the procedures and variables related to the studied process. Therefore, blasthole drill customizations justify a new process map for bit replacement.

2.2. Ergonomic analysis using NIOSH lifting equation

As presented in the previous sections, the bit replacement has several variables related to the lifting of tools during the professional activity. In this case, it is necessary to lift objects over 23 kg, to walk and to rotate the trunk carrying these objects. According to Waters et al. [14], the use of the NLE is indicated to measure the level of ergonomic risk of this type of professional activity. This methodology of ergonomic analysis is able to measure the level of ergonomic risk through a system of equations that relates the activity frequency, distance, geometry and load lifted during the tasks [16].

The primary output of the NLE is the Recommended Weight Limit (RWL), which defines the maximum acceptable load

(measured in kg). This weight represents the maximum load that a person can handle without ergonomic risks or the possibility of developing musculoskeletal disorders. Table 3 presents each of the parameters necessary to calculate the RWL. These parameters, obtained through a data collection, are represented in the NLE by the multipliers. The multiplier definitions are available in the multiplier equations column. The variables HP, VP, DP and AP described in Table 3 match the dimensions shown in Fig. 2.

Each task of the bit replacement process, described in Table 2, should be evaluated after all the task parameters

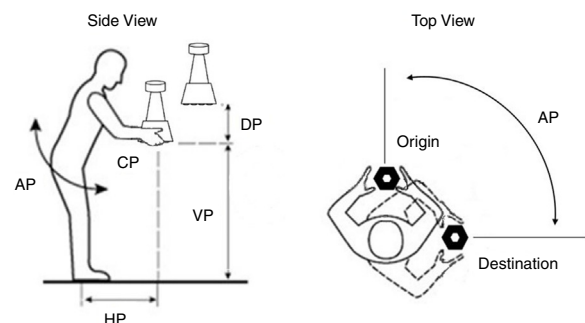


Fig. 2 – NIOSH Lifting Equation parameters for bit replacement tasks presented by side view and top view.

Table 4 – NIOSH Lifting Equation guide.

Results	Definition and units	Ergonomic risk analysis
FIRWL	FIRWL (kg) = RWL/FM	Useful for FILI calculation and analysis
LI	LI = AL/RWL	LI ≤ 1 – low ergonomic risk LI > 1 – high ergonomic risk
FILI	FILI = AL/FIRWL	FILI ≤ 1 – low ergonomic risk FILI > 1 – high ergonomic risk

Source: Waters et al. [13].

have been collected. Each variable has a definition, unit, and an equation that defines the corresponding multiplier. The multipliers represent the variables used to calculate the RWL, according to Eq. (1). By setting the RWL value, the NLE generates results that can measure the ergonomic risk level of the bit replacement. These results are influenced by the maximum load lifted, average load lifted and duration of each task.

$$RWL = LC \times HM \times VM \times DM \times AM \times FM \times CM \quad (1)$$

The first multiplier of the NLE to obtain the RWL is represented by a constant load of 23 kg. This value represents the recommended load (limit) for lifting. Loads above this limit generate risk of injury. This statement is accepted by all operators of rock drilling operations of the studied mine. The other multipliers weigh the constant load and allow a specific analysis of each task. The main results of the equation, obtained through the RWL value, are represented by the Frequency-Independent Weigh Limit (FIRWL), Lifting Index (LI) and Frequency-Independent Lifting Index (FILI). The LI and FILI results are functions of the average load lifted (AL) measured in kg. The average load (AL) of each bit replacement task is available in Fig. 1. After data collection, all these results were obtained by equations presented in Table 4.

The evaluation of the LI value is relevant, since it eliminates the influence of loads in the activity analysis. Thereby, other important parameters are also considered in the ergonomic analysis. An LI value below 1.0 indicates that the activity has a low ergonomic risk and may be considered normal. LI values equal to or greater than 1.0 indicate that tasks have a high ergonomic risk. As the LI value increases above 1.0, it also increases the probability of development of low back (lumbar) injuries [17]. FILI and FIRWL results eliminate the influence of frequency on activity by measuring the level of risk for a single task repetition. However, the FILI result is calculated based on FIRWL. Therefore, the evaluation of bit replacement ergonomic risk is carried out using the FILI value. The evaluation by the value of FILI and LI is justified by weighing frequency and load of the tasks connected to bit replacements. Both indexes are dimensionless.

Table 5 presents the results of the NLE for the 9 tasks mapped in Fig. 1. The bolded values indicate results above the critical limit of ergonomic risk. The LI results indicate that almost all tasks have significant ergonomic risk, regardless of the influence of loads. This ergonomic risk was only disregarded for tasks using the level support, which has a load of 5 kg. The FILI index results also reinforce the presence of ergonomic risk in most activities.

Table 5 – NIOSH Lifting Equation analysis using LI and FILI.

Task	RWL (kg)	FIRWL (kg)	LI	FILI
A	14.42	15.34	2.43	2.74
B	16.02	17.04	1.06	1.0
C	14.42	15.34	1.66	1.56
D	15.22	16.19	0.33	0.31
E	12.29	13.08	1.84	3.21
F	14.42	15.34	2.43	2.74
G	16.86	17.94	1.01	0.95
H	15.18	16.15	1.58	1.49
I	16.02	17.04	0.31	0.29

3. Development of the bit replacement device

After the ergonomic analysis, it has been proven that the conventional bit replacement has meaningful risks. Considering the NLE evaluation, through the results of Table 5, it is possible to indicate that the employees charged with bit replacements can develop low back (lumbar) injuries in the medium or long term [18]. Against this conclusion, the present work seeks to reduce the identified risks. According to the task characteristics, these risks are enhanced by the load lifted, the need to walk carrying high loads and the tool position when handled. The last characteristic refers to employees' posture during the bit replacement, where it is necessary to bend to position some components.

As previously identified, it is necessary to adjust the blast-hole drill to eliminate the need to lift high weight components. The blasthole drill itself has a winch installed at the top of the drilling tower, as shown in Fig. 3 with the number 1. But for this winch to be used for hoisting in the bit replacements it is necessary that tools and accessories are close to the drilling platform, indicated with number 2 in Fig. 3. The winch operating area is represented by a cone with a vertex at point 1 (Fig. 3) and base at the platform (point 2, Fig. 3). With all tools available within the winch range, the need to walk carrying the

**Fig. 3 – Blasthole drilling operation in an open pit mine.**

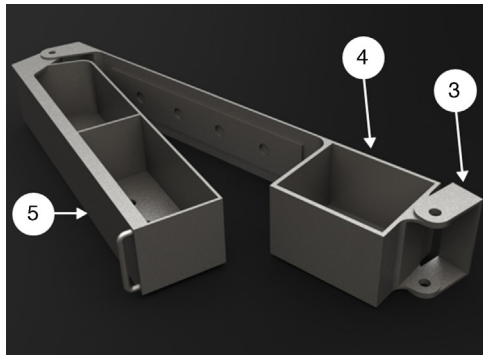


Fig. 4 – Bit replacement device project.

high load is eliminated. Fig. 3 shows the elevation between the drilling platform and the floor. This elevation is 0.9 m and the whole process of switching happens on this platform. According to operators' reports, there is great discomfort generated by frequent use of the ladder to access the platform. Even after access, operators need to bend over and move in a very small space.

3.1. Ergonomic device design and implementation

After collecting the accessory replacement details, technical characteristics of blasthole drills and available lifting equipment; it was possible to design the bit replacement device. The development of the docking device for tools and accessories was carried out using computer graphics simulation tools. Tools must be available between the chest and waist of an operator standing on the drilling platform. Additionally, this device must be retracted after use to allow new bit storage during operation. Fig. 4 shows the simulation results in a computational environment. The main simulation result is to know the device's total weight, dynamics and influence on the blasthole drill balance. Before installing the device, it is necessary to measure the influence in an operational condition. Even with several bits and tools, the device carries a load of about 300 kg. Thus, the evaluation indicated that the device does not imply any threat to the safety and equipment efficiency of 26 t weight.

As shown in Fig. 4, the bit replacement device must be installed near the drilling platform. The device fixation point in the equipment is indicated by the number 3 in Fig. 4. This fixation is made on the left side of the drill, close to the platform. The number 5 indicates the location of the bits and tools insertion holder. There is a specific support for new bits and another for worn bits. The number 4 indicates the lifting adapters' location. With the device installation, operators must use lifting adapters for the winch. Fig. 5 shows the device installed in a blasthole drill. The image shows an operator hoisting the bit using an adapter. It is important to note that all tools and bits are available on the device between the waist line and the operators' chest. This installation eliminates the need for manual lifting of tools and accessories.



Fig. 5 – Bit replacement device in operation.

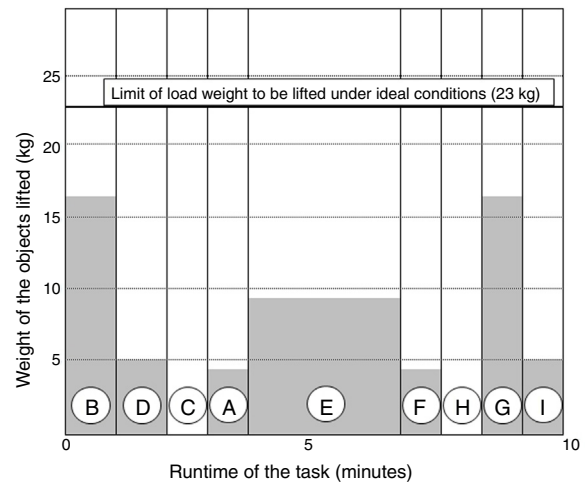


Fig. 6 – Process map of new procedure for bit replacement.

4. Results and discussion

Tools adapted to employees' biomechanical characteristics are necessary to provide ergonomic conditions in work environments [18]. The tasks described in Table 2 continue to be performed in the new bit replacement procedure, shown in Fig. 5. The customization installed in the blasthole drill eliminated walks carrying loads, manual lifting and frequent change of level (platform access by ladders). A comparative evaluation between ergonomic analysis before and after modifications made in the working environment is needed to verify the elimination or control of ergonomic risks [16]. Fig. 6 shows the process map of bit replacement using the mechanical device with a new procedure.

The process map of new procedure for bit replacement presents significant changes compared to original procedure. The new device requires some changes in the sequence of tasks, starting with placement of the coupling lock. This tool is available in a location close to the platform without the need for operators to squat. The next task is to place the level support on the platform without any changes. Tasks C, A, F and H underwent significant changes of procedure and duration. These tasks started to be realized with the use of a

Table 6 – NIOSH Lifting Equation analysis using LI and FILI for new bit replacement procedure.

Task	RWL (kg)	FIRWL (kg)	LI	FILI
B	17.04	17.04	1.0	1.0
D	16.19	16.19	0.31	0.31
C	17.04	17.04	0.06	0.06
A	17.04	17.04	0.06	0.06
E	16.15	16.15	0.56	0.56
F	17.94	17.94	0.06	0.06
H	17.94	17.94	0.06	0.06
G	17.04	17.04	0.29	0.29
I	17.04	17.04	1.0	1.0

mechanical device that allows the hoisting of bits and chain wrenches using the winch. Consequently, each of these tasks began to run in 40 s representing a 20% reduction. With all the tools available in the right place at the right time, excessive effort and rework were eliminated during accessory switching. Task E underwent a significant change in working conditions, because there was a reduction of load lifted from 14 kg to 9 kg. This 43% load reduction is justified by the use of the new mechanical device. There was also a reduction in the task duration to 3 min, which represents a reduction of 80%. After the bit replacement, the device is retracted, and the coupling lock and level support tools are directed to their holders, according to tasks G and I.

As established in the methodology, it is necessary to evaluate the ergonomic analysis of new bit replacement procedure. Table 6 presents the results of this new ergonomic analysis using the NLE. Due to the customization made in the blasthole drill, a change in the sequence of tasks was made. The new process map shows no ergonomic risk during bit replacement using the mechanical device. All tasks have LI and FILI indexes less than or equal to 1.0. However, tasks B and I require attention and follow-up from mining management. These tasks require a short walk handling a 17-kg tool. Despite the load complying with recommendations (RWL and FIRWL), the LI and FILI indexes are close to the limit of criticality. Arjmand et al. [19] states that it is possible to develop some types of lesions under certain operating conditions, even with the LI and FILI indexes below the criticality limits. Facing this possibility, the employees were monitored for 18 months after the device installation. Through surveys, interviews and medical examinations no injuries or discomforts were detected after the monitored period. Future task revisions, without specific analysis, may expose employees to ergonomic risks again.

4.1. Uncertainties and limitations

After the installation of the new bit replacement device, a new operating procedure must be followed by all operators enabled to operate a blasthole drill. This device becomes a safety component, and any failure may represent the unavailability of the equipment. It is still not possible to establish the durability of each component that makes up the device. It is also not possible to establish a maintenance plan. This requires an operating time of 2–3 years. It is very important that the device is used according to operating procedures developed by the team of instructors and safety engineers. Even so, the device was developed with a lubrication system on the bearings. This

is a recommended practice by equipment manufacturers for devices with mechanical systems allowing the lubrication of moving parts during preventive maintenance. This is the only applicable maintenance recommendation to date.

Another device restriction is the need for manually positioning and retracting the device by operators. There is no hydraulic or electrical system for this task. Correct positioning and locking does not have any type of alarm or automation that alerts the operators to possible misuse. There are some automation solutions that can be evaluated for future tests. Locking alarms and sensors that measure any structural deformations can be tested. As the tools and accessories are at one end and the fixing point is at another end, a leverage effect may affect welding and deform the device structure. Deformation sensors can support maintenance plans and future improvements in the device indicating how and when deformations appear.

5. Conclusion

After completion of industrial-scale tests developed during 18 months, the bit replacement device was acknowledged to be an essential element in rock drilling by the blasthole drill operators. With the introduction of the new ergonomic device, the risk level of the bit replacement procedure was below 1.0 (criticality limit) for the LI and FILI indexes. This is a significant improvement compared with the manual replacement method that has 78% of the tasks with ergonomic risk above the critical limits. After the successful installation of the device, training and testing during 18 months, the company decided to install the device in the other blasthole drills used in the mine.

Besides the ergonomic risk reduction, the new device operation also achieves a replacement time reduction. By comparing the process maps of the manual and mechanical procedures, there is a clear reduction in bit replacement time. The manual procedure requires an average of 25 min for each switch, while the mechanized procedure takes about 10 min. These results overthrow the hypothesis of operational efficiency loss after the actions of reducing ergonomic risks.

Other activities may present ergonomic risk during drilling operation such as drill switching and down-the-hole hammer handling. Future studies should also evaluate the life cycle of the mechanical bit shifter and its components. Possible adaptations that eliminate ergonomic risks may represent new opportunities for performance improvement.

Conflicts of interest

The authors declare no conflicts of interest.

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