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Evaluación muscular comparativa del uso de un exoesqueleto en la operación de armado de andamios, caso de estudio

INDUSTRIAL ENGINEERING

A comparative muscular assessment of the exoskeleton in a scaffold building operation, case study

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Abstract

The job in medium and high voltages lines for the Enel-Codensa Organization has generated discomfort reports in parts of the body, such as the shoulder and back also has been develop increase in absenteeism due to the development of occupational diseases such as lumbago and illnesses in the shoulder. The muscle evaluation of this case study was applied to a group of workers from the Colombian company, Enel-Codensa, which has an interest in improving the

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working conditions of its workers including exoskeletons in the development of its work. To achieve this, eight muscles were evaluated in which electromyography (EMG) was used in 20 volunteer participants, consisting of 12 electrical technicians and eight volunteers. The aim of the study was to determine whether a decrease in muscular effort occurred when the workers used the exoskeleton, to compare experienced and inexperienced subjects, and ultimately to analyze whether muscular activity varied with the use of an exoskeleton. As a result, muscular effort was lower in all the muscles when using the exoskeleton. However, the activity remained above 10% of muscular effort on average, which can generate muscular fatigue if such activity is maintained during an 8-hour day. The analysis showed that there is no difference when performing the activity with or without an exoskeleton except for the flexor carpi radialis muscle. Alternatively, when comparing the two groups, experts, and novices, it was found that the muscular activity of the experts was greater by 1%. As the study was performed, it was found that among this group, there was not an equality of measurements in six of the eight muscles. In conclusion, the scaffold erection test demonstrated muscular effort in the forearm and arm for both samples. To reduce this muscular effort, it is recommended to provide tools or redesign the task.

Keywords*: Ergonomics, Electromyography, Working Conditions, Exoskeleton.*

Resumen

El trabajo de los lineros de media y alta tensión en la organización Enel-Codensa ha generado reportes de dolencias en partes del cuerpo, como lo son hombro y espalda y aumento de los ausentismos por desarrollo de enfermedades de laborales como los son los lumbagos y el manguito rotador. La evaluación muscular del caso de estudio se realizó a un grupo de trabajadores de la empresa colombiana Enel-Codensa, la cual tiene interés en mejorar las condiciones de trabajo de sus colaboradores, considerando la utilización de exosqueletos en el trabajo, con el fin de contrarrestar los elementos mencionados. Para lograrlo, se evaluaron ocho músculos. Se hizo uso de electromiografía (EMG) en 20 participantes voluntarios, doce linieros de alta tensión y ocho voluntarios. Lo anterior, con el fin de determinar si existe o no disminución en el esfuerzo muscular al usar el exoesqueleto; y comparar también si entre sujetos con experiencia y sin experiencia, la actividad muscular varia al usar el exoesqueleto. Como resultado se obtuvo que el esfuerzo muscular es menor en todos los músculos al usar el exoesqueleto. Sin embargo, la actividad se mantiene por encima del 10% de esfuerzo muscular en promedio, lo que puede generar fatiga muscular si se mantiene durante una jornada de ocho horas. El análisis estadístico de diferencia de medias dio como resultado que no existe diferencia entre realizar la actividad con o sin exoesqueleto excepto para el musculo Flexor Carpi Radial. Por otra parte, al realizar el comparativo entre los dos grupos, expertos y novatos, se encontró que la actividad muscular de los expertos es mayor en un 1%. Cuando se realizaron pruebas estadísticas de comparación de medias entre este grupo se no encontró igualdad de medidas en seis de los ocho músculos. En conclusión, para la prueba de armado de andamio, hay esfuerzo muscular en el antebrazo y brazo para ambas muestras. Para disminuir el esfuerzo muscular se recomienda brindar herramientas que contribuyan a una disminución de este o rediseñar la tarea.

Palabras clave*: Ergonomía, Electromiografía, Condiciones de Trabajo, Exoesqueleto.*

1. Introducción

Musculoskeletal disorders (MSD) are caused by workday efforts, which are mainly due to prolonged, maintained, and/or forced postures that are out of the neutral ranges. The working conditions for this type of activity are characterized as unstable and with vibration. All MSD's are caused by activities, such as manual material handling and repetitive movements [1,2].

In 2018, Colombia had 9.9 million people employed according to the Minister of Health. From this group, the occupational accident rate was 5.29 per 100,000 workers. The report of occupational risks presented in September 2019 by the national government showed that the electricity, gas, and water industries had a rate of 0.0028 accidents per 100,000 workers and a total of five diseases were reported in 2019. In this project with Enel-Codensa, a large electricity company in Colombia, exoskeletons were used to assist industrial workers. The use of this type of element is supposed to contribute to the worker's performance from an ergonomic point of view [3] by reducing the weight and tension load supported by the workers on medium and high voltage power lines.

There are two main types of exoskeletons: passive and active. Other derivations of these exoskeletons can be found on the market. They are also known as pseudo-passive and the hybrid (4). The use of passive exoskeletons supports manufacturing workers while reducing the risk of developing (MSD), which has been recently studied in the literature. Today, exoskeletons are used in various fields, such as medicine, manufacturing, and even in the military for very specific tasks, such as manual lifting of materials (5). In the literature, exoskeletons are considered personal protection elements that can help prevent shoulder injuries (6).

According to Michel's research in which they used electromyography (EMG) to analyze some activities in manual material handling and its results, they found a reduction of 40% of muscular activity in the back muscles during dynamic and static motion. In addition, they found that passive industrial exoskeletons help reduce low back load and seem to be very useful while undertaking upper body elevation activities (7). In a study in which they simulated work above the shoulders, they realized during the evaluation that the use of the exoskeleton modifies the muscular activation, such as the biceps, pectoral, and triceps brachii. Statistically, there is a difference in muscle activation when the exoskeleton is used when it is loaded (using a tool) or is load-free (8).

Finally, in another study, the use of different exoskeleton designs that support the shoulder and the weight of work tools for drilling tasks above the operator's head was analyzed. This study showed that the exoskeletons that support the shoulder reduced the maximum muscle load of the shoulder but did not significantly affect the quality of the work performed by the operator (5).

Accordint to a study carried out by Jonsson in 1988 showed that muscular activity exceeding 10% of the muscular voluntary contraction (MVC) assumes that there is muscular effort, and prolonging this effort for an eight-hour day can cause muscle loss or even muscle fatigue (8), this can happen in any type of job that requires muscular effort.

More recent studies in the literature (8-10), show that the use of passive exoskeletons for workers in the manufacturing industry helps to reduce muscleskeletical disordes (MSD). It was analyzed in various studies and according to the measurements of electromyographic signals (EMG), the muscle activity reduction goes up to 40% in back muscle activities during dynamic lifting and static retention (10). In a test applied on the proto-MATE exoskeleton with over fifteen participants, a significant reduction (between 18% and 42% activation) in three out of the eight evaluated muscles was found. In other muscles, a smaller reduction was also found when using the exoskeleton, which implies that the exoskeleton is effective in reducing physical demand (10). In a study developed for work involving the development of their activities above the head, posture and muscular activity in the upper limbs were evaluated in ten selected muscles. Using the exoskeleton contributed to facilitating activity for workers. The most drastic reduction in EMG amplitudes was observed in the deltoid muscles and the biceps brachii, which are the most important generators of the forces required to perform shoulder anteversion (11).

Furthermore, it has been indicated that passive industrial exoskeletons are intended to support or unload the lumbar region and appear to be quite successful for dynamic lifting activities, such as static retention. In the work presented during the assembly tasks, reductions in muscle activity between 35% and 38% and less discomfort in the back when wearing the exoskeleton compared to the same task without using this equipment were found [8]. In the reported work [5], the influence of different exoskeleton designs that support the shoulders and the weights of work tools for drilling tasks above the operator's head were analyzed. In this report, it was found that the exoskeletons that support the shoulder reduce the maximum muscle load of the shoulder but do not significantly affect the quality of the work performed by the operator.

With the over-the-head scenarios, this type of activity is conducive to developing MSD, and it has been shown that the use of exoskeleton systems contributes to reducing occupational diseases of the MSD type. The interest in this type of injury shown by the organization Enel-Codensa with the aim of helping workers performing these activities around the country and making the evaluation simple to its operators, more specifically for those who work on medium and high voltage lines, using exoskeleton as a tool to improve their working conditions. For this study, the evaluation of muscular effort with risks in upper limbs was carried out as it was developed in other economic sectors in Colombia, such as in the case of flowers and coffee workers [12-15]. To complete the case, a simulated situation above the shoulders was applied [16]. For the study case, the task was also performed with and without exoskeleton doing the similar tests performed in a rehabilitation center in Lecco, Italy [10].

2. Methodology

The objective of the case study was to perform a muscular evaluation while simulating the assembly of medium and high voltage line towers during the construction of a scaffold for work performed at heights. The sample included twelve workers from the Enel-Codensa company (experts) and eight novice volunteers (non-experts) from the Pontificia Universidad Javeriana (all men). All of them voluntarily participated by signing the informed consent that was submitted to the research and ethics committee of the Faculty of Engineering of the Pontificia Universidad Javeriana with document identification number FID 317Aval CIE. Table 1 Demographic data shows the general participant characteristics.

To accomplish the goal in the study case, a muscular evaluation with electromyography was applied while an experiment was conducted. The sensors were placed following the instructions of the electromyography guide and the European Association for Electromyography Surface Electromyography for the Non-Invasive Assessment of Muscles (SENIAM) [17,18]. The muscles that were measured in the development of this activity were the carpi radial and ulnar extensors (ECR and ECU, respectively), the carpi radial and ulnar flexors (FCR and FCU, respectively) the biceps, the middle deltoid, the upper trapezius, and latissimus dorsi.

Table 1 *Demographic data of Study Participants*

Element	**Value**	**Standard Deviation**
Mean age	37.35	11.17
Maximum age	59	
Minimum age	21	
Mean Height (cm)	169.42	6.46
Maximum Height (cm)	180	
Minimum Height (cm)	157.7	
Right-handed	16	
Left-handed	4	

The test consisted of assembling a scaffold with and without an exoskeleton with ten minutes of rest as shown in Figure 1 Set of tests with instrumented subjects. The height for the scaffold use on this test was 2.0 m. The task was to build a scaffold following instruction made by the investigators, without the exoskeleton and using the exoskeleton. To participate in the study, the subjects did not have to carried out any physical activity. Therefore, measurements were taken first thing in the day, to ensure that they did not have muscle fatigue. Between measurements the subject rested for 45 minutes before they started again. A session consists on prepare the EMG and MOCAP system (Motion Capture System) (15 minutes), the instrumentation of the subject and background record (60 minutes), MVC registration (25 minutes), a rest before the first test (15 minutes), test without exoskeleton (15-20 minutes), a second rest between activities (30 minutes), test with exoskeleton (15-20 minutes). The exoskeleton used in the lab measure was the COMAU MATE. The exoskeleton tested in this study is a comercial version using in manufacturing systems, it assists the worker performing assembly in a production line.

According to the manufacturer, "the MATE exoskeleton is aligned with the flexion-extension axis of the human shoulder creating both a comfortable interaction and an extraordinary human-machine synergy". The MATE exoskeleton has a total weight of 3,5 kg and have four main components, 1) the torque generator boxes that produce the gravitational torque to support the arms' weight, 2) the pHMI, which connects the device to the human body at the waist, trunk, and arms and is responsible for transferring the forces to the human body and supporting the reaction forces, 3) the kinematic chain of pDOF, which is responsible for self-aligning the robotic and human joint axes, 4) a set of size regulations that allow adjusting the exoskeleton to fit users with different anthropometries [10].

Figure 1 *Set of tests with instrumented subjects*.

The signals were encoded and transmitted in the American Standard Code for Information Interchange (ASCII) format and processed using algorithms in the Matlab R2013a/R2018a program (United States), the root mean square (RMS) signal was estimated from a 200 ms moving window and normalized with the maximum voluntary contractions (MVC) recorded for each muscle at the 5% and 95% static, mean, and dynamic levels were estimated in the amplitude probability distribution function (APDF), following the SENIAM recommendations [18].

The sensors were located as can be seen in Figure 2.

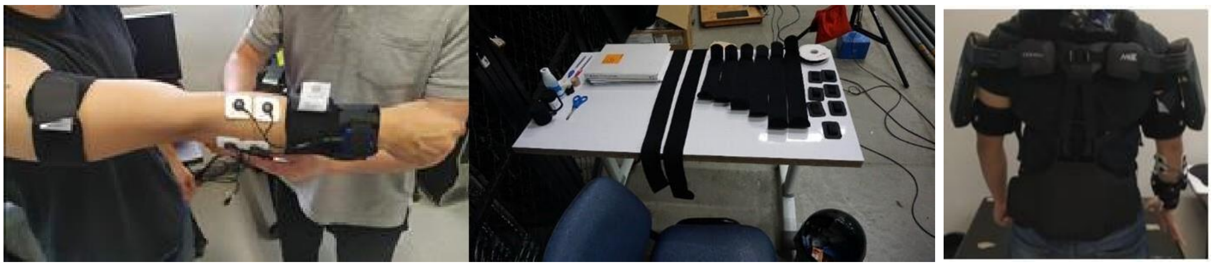
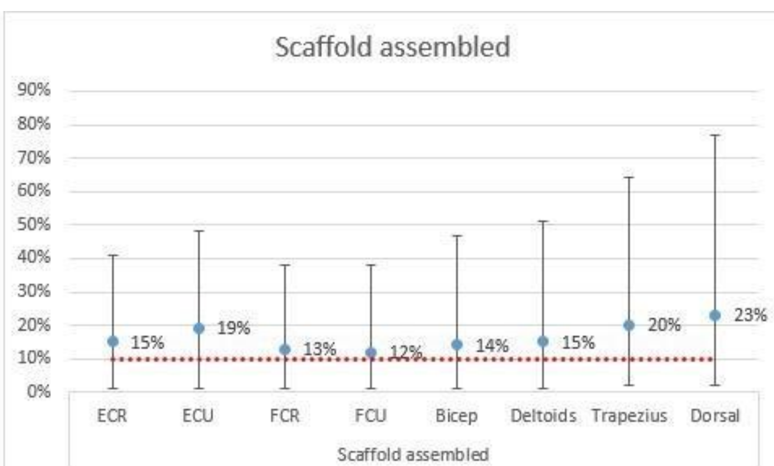


Figure 2 *Instrumentation set of the electromyograph (EMG)*

3. Results

As a result, the use of assembling a scaffold with the support of an exoskeleton is only one percentage point lower than when a worker performs the same activity without the support of one, reference Figure 1 Comparative muscular effort between the test with and without the exoskeleton. If the activity is maintained above 10% with respect to the maximum voluntary contraction on average, this activity could cause muscular efforts, which can generate fatigue if it is maintained over the course of an eight-hour day [19].



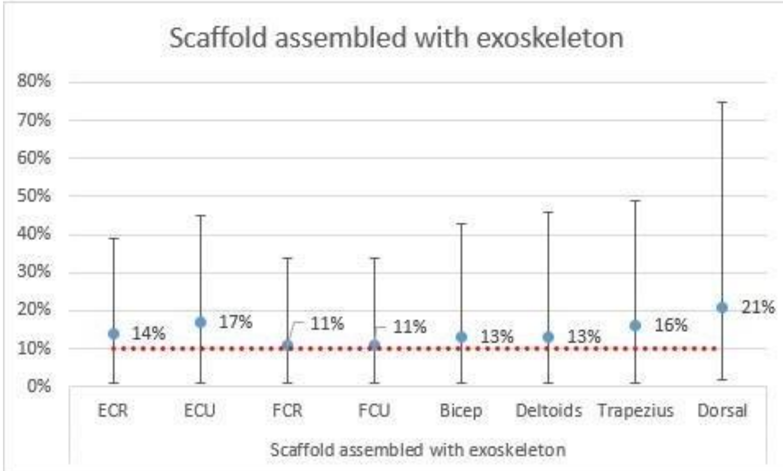


***Figure 1** Comparative muscular effort between the test with and without the exoskeleton*

Additionally, a comparison was made between the two tests using an analysis of means between the collected data in which it was established that both tests have the same mean as a null hypothesis. For this hypothesis, a normality test was carried out in order to perform the respective test. Our findings allowed us to see which of the muscles followed a normal distribution in order to make the comparison. In cases in which p-value (sig.) was < 0.05, non-parametric tests were performed.

***Table 2** Normality test per test*

Normality Test		Shapiro–Wilk		
Muscles	Tests	Statistic	Gl	Sig.
ECR	Scaffold assembled with exoskeleton	0,946	20	0,304
	Scaffold assembled	0.927	20	0.137
ECU	Scaffold assembled with exoskeleton	0.939	20	0.234
	Scaffold assembled	0.944	20	0.282
FCR	Scaffold assembled with exoskeleton	0.931	20	0.16
	Scaffold assembled	0.918	20	0.091
FCU	Scaffold assembled with exoskeleton	0.972	20	0.796
	Scaffold assembled	0.922	20	0.108
Bíceps	Scaffold assembled with exoskeleton	0.968	20	0.713
	Scaffold assembled	0.911	20	0.066
Deltoids	Scaffold assembled with exoskeleton	0.966	20	0.673

	Scaffold assembled	0.974	20	0.843
Trapezius	Scaffold assembled with exoskeleton	0.956	20	0.461
	Scaffold assembled	0.878	20	0.016
Dorsal	Scaffold assembled with exoskeleton	0.878	20	0.016
	Scaffold assembled	0.856	20	0.007
ECR: extensor carpi radial ECU: extensor carpi ulnar FCR: flexor carpi radial FCU: flexor carpi ulnar				

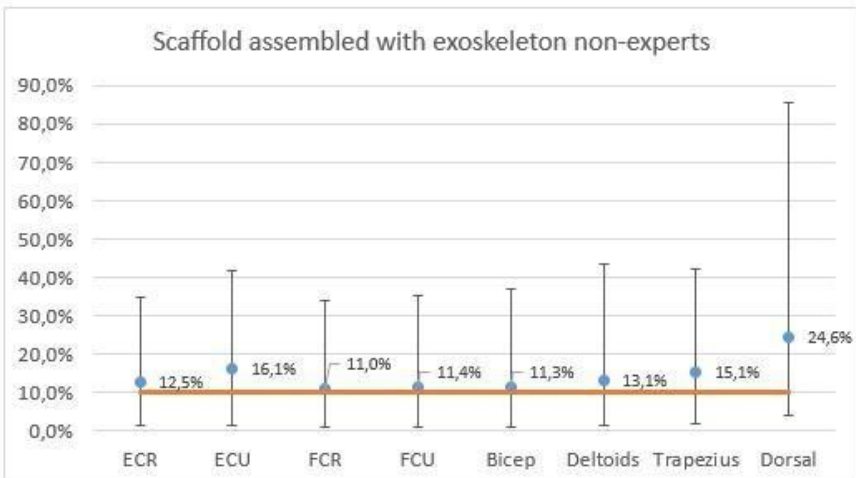
The significance values for all the muscles were > 0.05 of α are shown in Table 3 Mean comparison test which indicates that there is no difference with or without the exoskeleton when performing this activity for the exception of the FCR muscles in which their values were < 0.05.

Table 3 *Mean comparison test*

Muscles		**T-test for equal means**		
		T-test	**Gl**	**Sig. (bilateral)**
ECR	Equal variance	0.462	38	0.647
	Non-equal variance	0.462	37.387	0.647
ECU	Equal variance	0.803	38	0.427
	Non-equal variance	0.803	35.581	0.427
FCR	Equal variance	2.236	38	0.031
	Non-equal variance	2.236	37.997	0.031
FCU	Equal variance	1.757	38	0.087
	Non-equal variance	1.757	37.719	0.087
Bíceps	Equal variance	0.639	38	0.526
	Non-equal variance	0.639	37.916	0.526
Deltoids	Equal variance	1.122	38	0.269
	Non-equal variance	1.122	37.238	0.269
Tests statistic[a]				
	Trapecio			*Dorsal*
Mann–Whitney	*136.000*			*179.500*

Wilcoxon	*346.000*	*389.500*
Z	*−1.735*	*−0.555*
Sig. asymptotic (bilateral)	*0.083*	*0.579*
Sig. (2(sig. unilateral))*	*0.086[b]*	*0.583[b]*

Finally, a comparison between experts and non-experts was performed. The results show that the experts' muscle activity was greater than the non-experts when they were doing the scaffold building activity using the exoskeleton, this can happen because the muscles of the expert are used to lifting loads and have a greater amount of muscle fibers generating a greater muscle contraction. As is shown in Figure 3 Muscular activity comparison between experts and non-experts except in biceps and dorsal muscles.



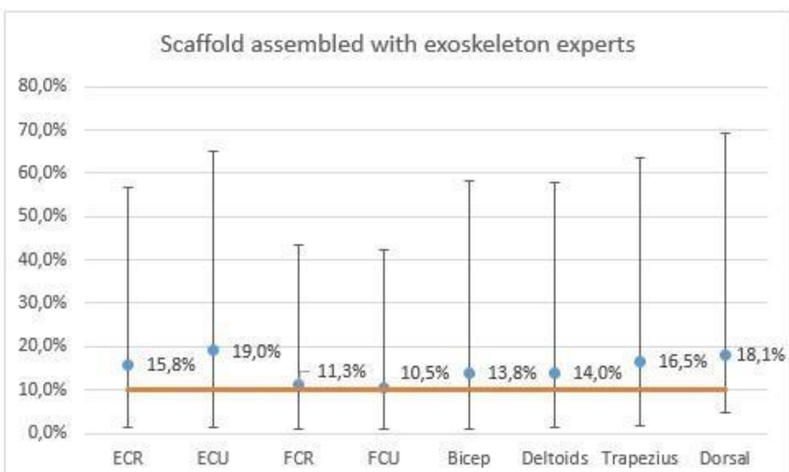


Figure 3 *Muscular activity comparison between experts and non-experts*

As a general analysis, the normality tests were carried out in Table 4.

Therefore, Student t-tests were performed. The results of the mean comparison between experts and non-experts are shown in Table 5. Comparison tests of means between experts and non-expert showed that six out of the eight analyzed muscles did not have equal means and showed less muscular activity in the non-experts. The muscles in which they share equal means were the ECR and ECU.

Table 4 *Expert and Novice Normality Tests*

Normality test				
		Shapiro–Wilk		
Expert and non-expert		*Statistic*	*gl*	*Sig.*
ECR	*Non-expert*	*0.963*	*8*	*0.836*
	expert	*0.967*	*12*	*0.882*
ECU	*Non-expert*	*0.948*	*8*	*0.687*
	expert	*0.914*	*12*	*0.239*
FCR	*Non-expert*	*0.931*	*8*	*0.521*
	expert	*0.916*	*12*	*0.258*
FCU	*Non-expert*	*0.972*	*8*	*0.911*
	expert	*0.939*	*12*	*0.488*
Biceps	*Non-expert*	*0.866*	*8*	*0.138*
	expert	*0.940*	*12*	*0.496*
Deltoids	*Non-expert*	*0.952*	*8*	*0.729*
	expert	*0.903*	*12*	*0.171*
Trapezius	*Non-expert*	*0.986*	*8*	*0.986*
	expert	*0.934*	*12*	*0.430*
Dorsal	*Non-expert*	*0.850*	*8*	*0.095*
	expert	*0.861*	*12*	*0.050*

Table 5 *Comparison of means between experts and non-experts*

Comparison of means between experts and non-experts				
		T-test for equal means		
Muscles				
		T-test	*gl*	*Sig. (bilateral)*
ECR	*Equal variance*	*2.204*	*18*	*0.041*
	Non-equal variance	*2.426*	*17.934*	*0.026*
ECU	*Equal variance*	*2.134*	*18*	*0.047*
	Non-equal variance	*2.267*	*17.687*	*0.036*
FCR	*Equal variance*	*0.349*	*18*	*0.731*
	Non-equal variance	*0.326*	*11.634*	*0.751*
FCU	*Equal variance*	*−0.695*	*18*	*0.496*
	Non-equal variance	*−0.649*	*11.722*	*0.529*

Biceps	*Equal variance*	*1.190*	*18*	*0.250*
	Non-equal variance	*1.089*	*10,839*	*0.300*
Deltoids	*Equal variance*	*0.429*	*18*	*0.673*
	Non-equal variance	*0.413*	*13.111*	*0.687*
Trapezius	*Equal variance*	*0.508*	*18*	*0.618*
	Non-equal variance	*0.527*	*16.932*	*0.605*
Dorsal	*Equal variance*	*−1,035*	*18*	*0.314*
	Non-equal variance	*−0.945*	*10.741*	*0.366*

4. Discussion

For the case study, a method was used determine and evaluate the working conditions of the midline and high voltage linemen during tower assembly exercise. The tests were simulated in a study under controlled conditions, and this study serves as a starting point for future research for this or similar activities. In this study, it was possible to identify the risks of muscular efforts to which workers and people who are not experts in labor may be exposed. It was shown that the muscles of the forearm and arm are constantly exposed to risk. In the simulation carried out in the research by Abdelmomen and others in addition to the tests also carried out in this study, it was concluded that it is necessary to continue working on exoskeleton re-design for security conditions since this study included work above normal heights and the need to transport elements while working together and using the exoskeleton [(5)].

According to different laboratory studies, it has been shown that there is a statistically significant difference between using the exoskeleton or not using it. According to this statement, the use of the exoskeleton in these activities help reduce of muscle activation [(10,16)]. The results of this study show that although the difference in muscle activation is smaller, it is statistically significant; therefore, it is assumed that the muscles present different activation rate. Although a drastic reduction in the biceps and deltoid muscles was found in the study of overhead tasks [(11)], in the trial test, this reduction only was one percentage point lower when using or not using the exoskeleton.

Although the test focused on the activity performed by the technicians who were performing scaffold assembling for use in tower assembly, this study only evaluated the muscular stress conditions in a similar controlled activity, which was scaffold assembly. It is necessary to apply the evaluation under real conditions, which would imply making adjustment to the exoskeleton so that it can be used in work at above normal heights. It is also necessary that the workers have all the safety clothing necessary to carry out the activity. Currently, the workers use mechanical tools for the development of this activity, but the implementation of other types of tools could benefit the improvement of muscular effort conditions.

Finally, comparing the results obtained with the study applied by Pacifico and others, where they found that the use of the passive exoskeleton in an automobile assembly manufacturing activity, the muscle activity in the upper limbs is much lower when using the exoskeleton than without it. in muscles such as the anterior and medial deltoid, the trapezium, and the pectoralis major, statistically tests, additionally they found percentage differences ranging from 2% to 40% in the muscles evaluated [(10)]. For the study case carried out on the activity of assembling a scaffold, statistics difference was found when using the exoskeleton or not on six muscles, just in two muscles the statistics difference was not found in the trapezius and in the dorsal. However, in the descriptive statistics analysis of the data, it is found that on average there are reductions between 1% and 4% in the muscles when using the exoskeleton. Although the exoskeleton was proved in manufacturing lines, like flow shops, for this activity that consist in the scaffold assembling, simulating the assembling of electrical towers, the use of the exoskeleton benefits in the reduce of muscle activity.

It is also known that the risks will not disappear; rather, the probable risk is transferred to another region of the body, and it is necessary to use different work methods or technology to improve the performance of the activity under different work conditions.

4. Conclusion

In summary, this case study shows that muscular effort in the forearm and arm are required while assembling scaffolding towers for medium and high-tension power lines. Similarly, it also shows that muscle activity is lower with the use of an exoskeleton. Although the statistical differences were found as to whether the use of exoskeleton helps to decrease muscle activity, this study attempts to find different approaches to achieving the goal of reducing muscular activity. Some examples include providing other types of tools to workers, reducing material loads, parts with the same resistance and less weight, and/or considering other elements that were not affected in the study, which implies a redesign of the activity.

On the other hand, when comparing the subjects between workers and volunteer novices, it is evident that the second group needed less muscular effort than the workers. Although only two muscles were statistically evaluated, the same findings are assumed in all the other muscles.

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