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ABERGO

VEGETATION PRUNING ACTIVITY PERFORMED BY LIVE LINE ELECTRICIANS: WORK AND CLUSTER ANALYSIS APPLIED TO BIOMECHANICS.

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ABSTRACT

This article aims to comprehend the vegetation pruning work performed by Live Line Electricians (LLE). To achieve this, we applied Ergonomic Work Analysis (EWA) and cluster analysis to identify patterns and clusters in cervical segment movements during the activity, utilizing a prototype support for hydraulic pole saws and without the support. The analysis took place in a laboratory environment. The study explored the k-means technique and its application in identifying two distinct clusters in the analyzed data. The results indicate a statistically significant difference in cervical angles between LLEs who used the support prototype and those who did not. The prototype resulted in lower angles, suggesting a more suitable posture during pruning activity. Cluster analysis revealed the existence of these two groups, providing a solid foundation for identifying trends and patterns related to support usage. In the context of combined ergonomic exposures, the study emphasizes the relevance of cluster analysis in identifying subgroups associated with different levels of musculoskeletal pain. Similarly, cluster analysis in this study provided a refined understanding of cervical movement patterns during vegetation pruning. In summary, cluster analysis proves to be an effective tool for identifying intrinsic patterns in biomechanical and ergonomic data related to vegetation pruning activity. The results reinforce the importance of the support prototype in reducing cervical overload, highlighting its significance for the health and safety of electricians performing this activity.

Keywords: Activity Ergonomics; Biomechanics; Live-Line Electrical Worker

1. INTRODUCTION

The research presents partial results of a Research and Development (R&D) Program. It is known that this type of initiative stands out as an essential driving force in the complete cycle of the research, development, and innovation chain in the Brazilian electrical sector (Traldi et al., 2022). Its vision goes beyond a simple quest for knowledge, encompassing the materialization of innovative ideas, successful laboratory experiments, and the practical application of mathematical models, all converging towards tangible results. In this context, R&D programs play a fundamental role in driving collaboration between companies, providing an appropriate scale to transform concepts into tangible improvements, both in organizational performance and the quality of life of individuals (ANEEL, 2022).

In this context, cluster analysis emerges as a valuable tool. Over the decades, this statistical technique has played a crucial role in various disciplines. In the 1950s, notable statisticians such as Robert R. Sokal and Edward F. Sneath introduced innovative methods for numerical classification and data visualization, establishing the initial foundations of this approach (Sokal, 1963). As we progress into the 1960s, cluster analysis solidified as a prominent statistical technique, permeating diverse fields such as biology, taxonomy, and psychology. In this period, hierarchical clustering and agglomerative linkage methods were developed, enabling the construction of dendrograms representing the clustering structure of data (Sokal, 1963). This temporal advance not only outlines the evolution of cluster analysis but also underscores its growing relevance as an essential tool in various areas of study, including ergonomic investigations like the present one.

In the subsequent decades, cluster analysis expanded into areas such as computer science and pattern recognition. Partitioning methods like k-means were introduced to create fixed data partitions into clusters, making the method more accessible. With advances in computing, clustering algorithms became more sophisticated. In the 1990s, there was a surge of interest in data mining and machine learning, and cluster analysis became a central technique for knowledge discovery in large datasets. Since then, cluster analysis continues to be widely used in various fields, driven by data growth and advances in computing (Geng & Hamilton, 2006; Jain, 2010).

Cluster analysis is defined as a statistical technique used to identify patterns and structures in complex datasets, aiming to group similar objects into clusters. It is an unsupervised learning technique, meaning there are no pre-defined labels or categories for the data, and the algorithm is responsible for identifying patterns and grouping them based on their characteristics (Jain et al., 1999).

The medical field already employs this technique due to large and complex biomedical datasets posing challenges for conventional hypothesis-based analytical approaches. Unsupervised data-driven learning can identify intrinsic patterns in these datasets (Eckardt et al., 2023). Many studies use cluster analysis as a useful tool for exploring patterns in cardiovascular diseases, contributing to improved risk stratification and patient management (Guedon et al., 2023; Kim et al., 2023; Lee et al., 2023; Mohammadi et al., 2023).

In the context of ergonomics, cluster analysis has been widely used to identify patterns, groups, and relevant characteristics in improving ergonomic conditions in work environments.

Jacquier-Bret et al.'s study (2023) applied this technique to analyze lymphatic massage performed by physiotherapists, decomposing it into generic postures (PG). Seven PGs were identified based on joint angles, variability, and relative frequency. The most common postures were PG6, PG4, and PG2, with predominant flexion observed in the trunk and neck regions, while shoulder flexion and abduction varied. RULA score analysis also showed differences between generic postures. These results emphasize the importance of monitoring massages and ensuring the use of proper postures to prevent musculoskeletal disorders. Thus, massages can be quickly assessed through a combination of generic postures for ergonomic analysis (Jacquier-Bret et al., 2023).

Another study analyzed the importance of combined ergonomic exposures at work for the development of musculoskeletal pain. Using the Workplace and Health Study in Denmark, researchers investigated 18,905 employees over four years. Through k-means cluster analysis, they identified nine clusters based on seven ergonomic factors. Using a weighted regression model, they observed that clusters with high combined ergonomic exposures showed a greater increase in neck-shoulder and lower back pain intensity. Additionally, clusters with high exposure to specific ergonomic factors also significantly increased pain. The results highlight the importance of combined ergonomic occupational exposures in the development of musculoskeletal pain and underscore the need for preventive approaches in the workplace (Andersen et al., 2021).

This study investigated balance recovery patterns after slips and their association with the probability of slip-induced falls. Sixty young participants were involved, subjected to unexpected slips while walking on a catwalk. Hierarchical cluster analysis was used to classify balance recovery patterns based on kinematic measures of both feet during the period from 100 to 300 ms after the slippery heel contact. Three distinct balance recovery patterns were identified, related to different levels of fall probability. These findings contribute to a better understanding of balance recovery mechanisms in slipping situations and can aid in the development and evaluation of fall prevention interventions (Hu et al., 2022).

Cluster analysis has been increasingly explored as a robust tool in the field of biomechanics. Thus, the use of this tool in conjunction with ergonomics suggests an interdisciplinary approach to addressing a given problem. Therefore, the study aims to understand the work of Live-Line Electricians (ELV) in vegetation pruning and conduct cluster analysis to establish groupings by considering cervical segment analysis in vegetation pruning, in a laboratory environment, with live-line electricians (ELV) with and without the aid of a hydraulic pruner support prototype.

2. METHODOLOGY

The study presents partial data from a Research and Development (R&D) project conducted in partnership between a private electric power company located in the interior of São Paulo, the Faculty of Applied Sciences (FCA) at UNICAMP, and a tool manufacturer for the sector.

A male Live-Line Electrician (ELV), 38 years old, right-handed, with 6 years of direct live-line work experience, and employed by the electric power company, participated in the research. The electrician voluntarily agreed to participate in the study through an Informed Consent Form. The research received approval from the ethics and research committee of UNICAMP – State University of Campinas, CAAE: 33462920.3.0000.5404. Opinion number: 4.151.017.

Initially, the method used was the application of Work Ergonomic Analysis (AET) (Guérin, et al., 2001) to understand the nature of the ELV's activity. Through a collective meeting with 12 ELVs, it was identified that vegetation pruning was considered the most critical in terms of difficulty, duration, and frequency. Subsequently, global and open observations of the activity were carried out in real situations, recorded in a field notebook, and validated through interviews after the task was performed due to the hazardous nature of interaction with workers during its execution.

For the biomechanical analysis of the movements performed in the activity, data collection was conducted with only one ELV in a controlled environment, in the biomechanics laboratory of FCA/UNICAMP. A 38-year-old right-handed male ELV, with 6 years of direct live-line work experience and belonging to the company's workforce, participated in this phase of the research.

In the laboratory, it was necessary to simulate the vegetation pruning activity environment performed by the electrician. For this purpose, a structure resembling a pole with a crossarm and attached tree branches was assembled using wooden cables and screws (Figure 1).

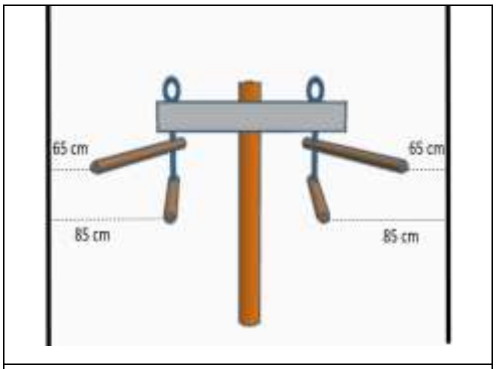
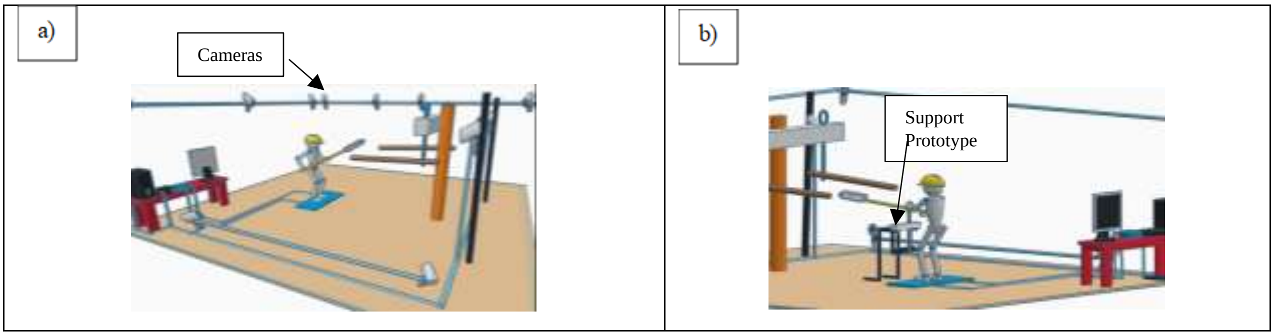


Figure 1. Laboratory setup for simulating vegetation pruning activity.

A data collection process was divided into two distinct moments. In the first phase, the Live-Line Electrician (ELV) was instructed to perform vegetation pruning movements according to their work routine, starting the pruning motion from the bottom of the branch and progressing towards the top (Figure 2a). In the second data collection phase, the ELV simulated the vegetation pruning activity similar to the first collection; however, this time, the movements were performed with the assistance of a prototype hydraulic pruner support (Figure 2b). During the vegetation pruning operation with the hydraulic pruner, the ELV made cuts on the branches in stages, allowing the branch to be pruned in proximal and distal cutting zones, labeled as E1 and E2 (left side of the ELV) and D1 and D2 (right side). Each cutting zone (15 cm in length) represents the specific location on the branch to be pruned, properly identified for standardization and easy visualization. Throughout the collection, the ELV performed 11 sets of complete movements, simulating the vegetation pruning movements by touching the branches from bottom to top and top to bottom in four predetermined zones along the branch, each measuring 15 cm.

For the collection of kinematic data, a motion capture system (Optitrack) consisting of 12 prime 17W cameras was used, configured with a sampling rate of 200 Hz to cover the entire capture area (Figure 2a; 2b). The full-body model used was proposed by (Leardini et al., 2011) for upper limb orientations (Wu et al., 2002) and lower limbs (Wu et al., 2005), following the recommendations of the International Society of Biomechanics (ISB) (Figure 2d).



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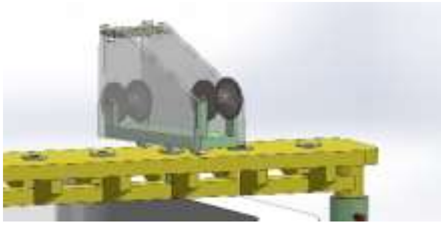

d)

Figure 2: a) 1st day of collection without the use of the hydraulic pruner support; b) 2nd day of collection with the use of the hydraulic pruner support; c) Image of the hydraulic pruner support prototype; d) Diagram with the bony landmarks to be used as a reference for the placement of surface markers.

The kinematic data were filtered using a 4th-order Butterworth digital filter with a cutoff frequency of 10 Hz. The Visual3D® software was employed for calculating kinematic variables, while other processing tasks were carried out in the Matlab® environment. RStudio software (version 4.1.2; RStudio Team, 2021) was utilized for statistical analysis. For the cluster analysis in this study, the k-means method was applied, and the number of clusters was determined through the silhouette method, which identified two clusters as the appropriate quantity to separate and group the sample (Hair et al., 2005; Rousseeuw, 1987).

3. Results and Discussion

3.1 Vegetation Pruning Task

A task of vegetation pruning involves precisely cutting various plant species that may intersect with electrical power lines, potentially disrupting their operation. This task is carried out by Live-Line Electricians (ELV) employed by the electric power company, using hydraulic pruners. ELVs are operators who work directly on energized power lines, exposing them to even greater risks of electrical shock and potentially fatal accidents.

Due to these risks, the use of various Personal Protective Equipment (PPE) is mandatory, including special clothing, boots, gloves, and other gear to mitigate potential hazards. Figure 3 illustrates and describes the PPE used by the electricians of the studied company.

Figure 3: Worker equipped with Personal Protective Equipment (PPE) for performing tree pruning activity**.**

The work performed by these electricians is also carried out in pairs. The executing electrician is the one who climbs into the bucket truck to perform the vegetation pruning operation. The second electrician works on the ground, observing the activity performed by the executor and alerting to any risks that may arise during the operation..

Figure 4: Worker performing vegetation pruning activity.

Through interviews conducted collectively and individually with Live-Line Electricians (ELV), it was identified that the activity involves a high degree of physical effort. Firstly, in terms of duration, this is an activity that can last from 1 to 3 hours or even days, depending on the tree.

Regarding physical exertion, ELVs reported that it is associated with the intensification and repetition of movements, findings that align with the study by Moriguchi et al. (2009). For the ELVs in the research, this factor results in a greater workload, especially in situations where the company includes pruning as a daily activity in the weekly schedule.

For ELVs, hand and arm movements are hindered by the Personal Protective Equipment (PPE) used, such as the thickness of gloves and protective sleeves. They also report significant physical efforts related to movements with one arm extended and the other flexed, or both extended or both flexed, above shoulder level, and trunk flexion. At the time of the research, all ELVs interviewed mentioned injuries and pain in the arms, forearms, wrists, elbows, and shoulders associated with vegetation pruning, as also noted by Gonçalves et al. (2021).

Added to this factor are the physical implications for the body due to constant exposure to climatic conditions of high temperature, heat, humidity, wind, and others, amplifying the workload (Traldi, 2022).

Although there is a standard procedure as an organizational norm describing how the task should be performed, it was identified that the postures adopted by electricians vary due to contextual work variables, such as the type of vegetation – thick or thin branches and trunks, longer or shorter, reach of vegetation, reach of the bucket truck, presence of venomous animals or bird nests, unevenness of the asphalt, power of the hydraulic pruner, among others. Within this analysis of real work (Guérin, et al., 2001), it is also possible to consider human variables that focus on the age of the worker, fatigue due to exposure to overload factors, experience, and others.

Research by Traldi et al. (2023) conducted in the electrical sector indicates that adapting postures and the way ELV work in tasks like this are crucial for the quality of work and the preservation of health and safety.

3.2 Cluster Analysis and Wilcoxon Test

A difference between the two samples, cervical segment in the sagittal plane during vegetation pruning without the prototype support and with the prototype support, was statistically significant ($p < 0.05$), as indicated by the Wilcoxon test ($p = 7.63045325667962e-38$). The effect size was considered large (Cohen's $d = 3.38$).

The results showed that when using the support prototype, the Live-Line Electrician (ELV) spent most of the time with lower angle values compared to values during vegetation pruning without the support (Figure 5).

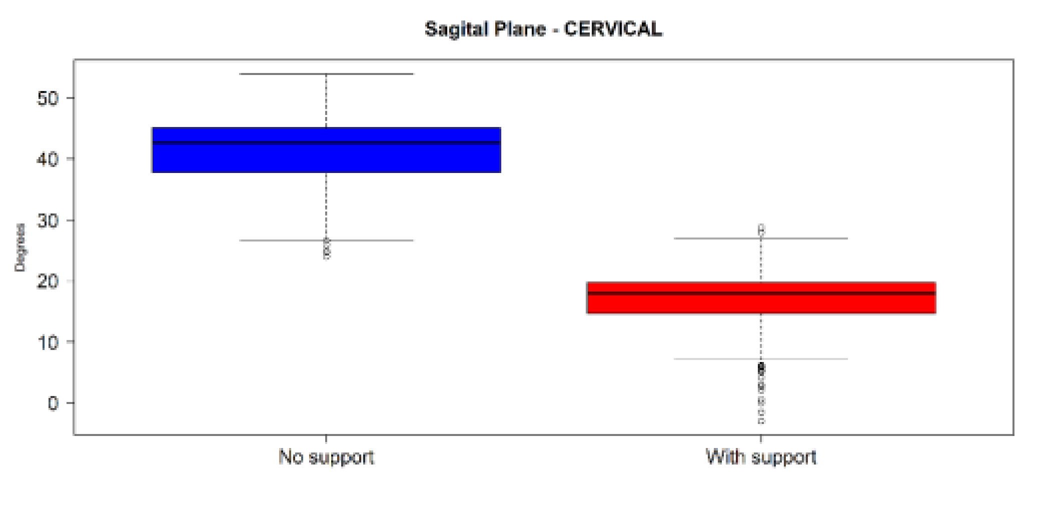

Figure 5: Boxplot with the results of the Wilcoxon test.

It was observed that the median angle values of the cervical segment without the assistance of the hydraulic pruner support prototype were approximately 147% higher than the values obtained with the support prototype. This discrepancy underscores the importance of the support prototype in reducing cervical segment angles and highlights its relevance in the context of ergonomics and the safety of workers using hydraulic pruners. The results of this study provide a solid foundation for implementing preventive measures and intervention strategies aimed at minimizing risks associated with harmful postures during hydraulic pruner operations.

After applying the K-means clustering algorithm, two distinct clusters were identified. These clusters were named Cluster 1 and Cluster 2, and the analysis focused on the angles of the cervical segment in the sagittal plane. Below, a description of the clusters found will be provided:

Cluster 1: "Without the aid of the hydraulic pruner support prototype" - This cluster contains a group of observations where the hydraulic pruner support prototype was not used or did not play a significant role. Instances grouped in this cluster share similar characteristics and behaviors, which differ from attempts with the use of the hydraulic pruner support prototype.

Cluster 2: "With the aid of the support prototype" - In this cluster, instances were grouped where the hydraulic pruner support prototype was used or played a significant role. Observations in this cluster share common characteristics indicating the use of the hydraulic pruner support prototype.

With the application of cluster analysis, the identification of these two clusters offers an approach to understanding diverse trends or patterns in the data associated with the adoption or non-adoption of the support prototype. This analysis plays a crucial role in providing a solid basis for decisions in identifying distinct subgroups within the studied population (Figure 6).

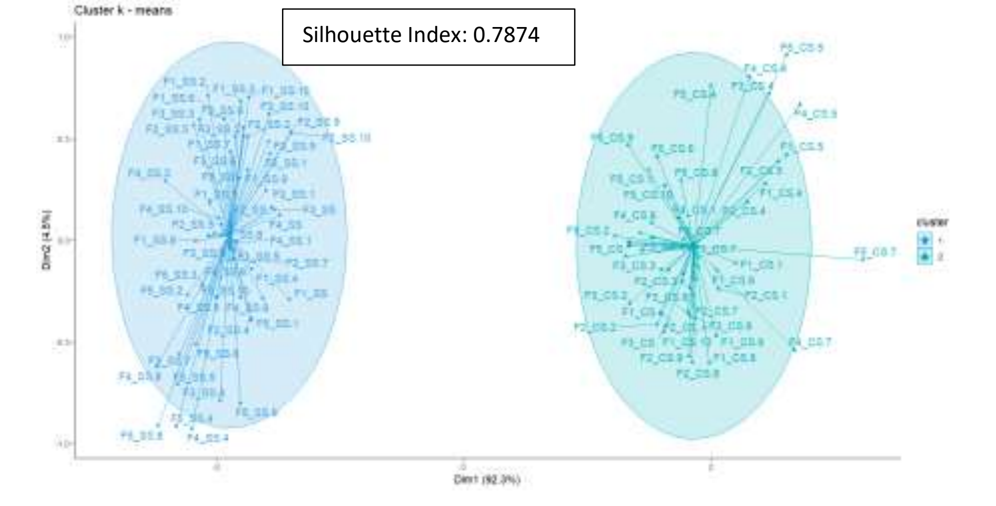

Figure 6: Result of the cluster analysis.

A cluster analysis applied to the data resulted in the formation of two distinct clusters, with a Silhouette Index of 0.7874. This value indicates a good separation and compactness of the clusters, reflecting the similarity of observations within each cluster and the dissimilarity between clusters. The high Silhouette Index value suggests that the data were grouped coherently, and the cluster analysis was effective in identifying patterns and structures in the data. These results promote a deeper and refined understanding of the relationships and characteristics present in the studied dataset, contributing to future investigations and decision-making based on the findings obtained through cluster analysis.

The study (Jacquier-Bret et al., 2023) employed the cluster analysis technique to examine common postures during lymphatic massage sessions performed by physiotherapy professionals. By discerning distinct postures based on joint angles, variations, and relative frequency, a more accurate ergonomic assessment was made possible, resulting in the mitigation of potential musculoskeletal problems. The findings highlight the effectiveness of cluster analysis in identifying significant patterns and groupings, with applicability to optimize ergonomic conditions in work settings.

Similarly, another study investigated the effects of combined ergonomic exposures on the development of musculoskeletal pain. Through k-means cluster analysis, researchers identified nine clusters based on ergonomic factors and observed that clusters with high combined ergonomic exposures had higher pain intensity. These findings underscore the importance of combined ergonomic occupational exposures and highlight the need for preventive approaches in the workplace. These results are consistent with the findings of the present study, which identified two distinct clusters based on cervical segment angles during vegetation pruning, with and without the aid of a support prototype (Andersen et al., 2021).

In the context of this study, an examination of balance recovery patterns after slips and their connection with the possibility of resulting falls was conducted. Using the hierarchical cluster analysis approach, researchers were able to discern three discrete patterns of balance recovery associated with different levels of fall risk. These findings enhance the understanding of the mechanisms underlying balance recovery in slip scenarios and have the potential to inform the creation of fall prevention strategies (Hu et al., 2022).

Similarly, the results of this study demonstrate the existence of two distinct clusters based on the cervical region positioning angles during vegetation pruning activity. These clusters suggest the presence of varied behaviors and characteristics, possibly related to the adoption or non-adoption of a support device in development. The use of cluster analysis in this context provides a more precise understanding of the relationships and intrinsic traits in the data, contributing to the identification of relevant patterns and structures.

From a methodological perspective, cluster analysis proved to be an effective approach in identifying intrinsic patterns and relevant groups in the analyzed datasets, contributing to a better understanding of the studied phenomena and providing important insights for musculoskeletal disorder prevention and informed decision-making. In terms of results, the present study presented data that align with the previously mentioned studies, which used cluster analysis in different contexts, such as the analysis of generic postures in lymphatic massage and the investigation of the effects of combined ergonomic exposures and balance recovery patterns.

4. CONCLUSION

The vegetation pruning task, as performed in the studied power company, presents significant impacts on the Live Line Workers (ELV), especially in terms of physical overload due to frequency, intensity, and repetitiveness. The research demonstrates how the actual work of electricians, as well as the postures and movements adopted by them in the execution of their tasks, result from contextual and human variability present in work situations.

The cluster analysis revealed the existence of two distinct groups: one composed of actions without the use of the support prototype and another with its use. The identification of clusters provided robust information about trends and patterns present in the data, allowing a deeper understanding of the characteristics and behaviors related to the use of the support prototype. These findings can provide a foundation for preventive measures and intervention strategies aimed at minimizing the risks associated with harmful postures during the operation of hydraulic pole saws. Thus, the cluster analysis, with a Silhouette Index of 0.7874, confirmed the effectiveness of the K-means method in identifying patterns and structures in the data, providing a solid basis for future investigations and decision-making based on the results obtained.

The results of this study revealed statistically significant differences in the angles of the cervical segment in the sagittal plane during vegetation pruning. When using the support prototype, a significant reduction in angle values was observed, resulting in a more suitable posture and lower cervical region overload. This finding highlights positive aspects of the support prototype from the biomechanical and ergonomic perspectives, aiming at the safety of workers using hydraulic pole saws.

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