MOTION CAPTURE FOR OPERATIONS ANALYSIS: A FOOTWEAR SECTOR CASE STUDY*

*María Juliana Cardona Márquez***
*Alex Mauricio Ovalle Castiblanco****

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ABSTRACT

The footwear sector in Colombia is predominantly composed of micro, small, and medium-sized enterprises (MSMEs) that rely heavily on manual processes and low technological adoption. This study aims to validate a methodology for motion-based operation analysis in real production environments, using optical motion capture (MoCap) systems integrated with virtual simulations. A footwear company's manual assembly was analyzed using four infrared cameras and reflective markers placed on workers' wrists and index fingers. The motion data were processed in MATLAB to recreate the operation virtually and identify types of movements and frequency . Results showed a total of 539 movements during a 90-second cycle, 215 operations (39.9%), 35 transports (6.5%), and 289 hold positions (53.6%). The average time per productive operation was 0.41 seconds, yielding an estimated productivity of 146 operations per minute. The virtual simulation highlighted a concentration of hand trajectories within the normal reach zone, indicating an efficient spatial arrangement. However, a high proportion of nonproductive movements revealed significant opportunities for method standardization and ergonomic design improvement. MoCap system implementation of enabled automated movement classification and trajectory analysis without manual segmentation, thus overcoming the subjectivity and limitations of traditional observation. Despite minor data losses due to environmental interferences, the system proved robust and applicable in an active industrial setting. This research demonstrates the feasibility of incorporating MoCap technology into time and motion studies for real manufacturing contexts, offering helpful tips for process redesign, operator training, and ergonomic assessment.

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** PhD. Universidad Autónoma de Manizales. Grupo de investigación Diseño Mecánico y Desarrollo Industrial. Caldas, Colombia. E-mail: mcardona@autonoma.edu.co Orcid: https://orcid.org/0000-0002-0760-6983

*** PhD. Universidad Autónoma de Manizales. Grupo de investigación Diseño Mecánico y Desarrollo Industrial. Caldas, Colombia. E-mail: movalle@autonoma.edu.co Orcid: https://orcid.org/0000-0002-1634-9456

Keywords: motion capture, manual assembly, work measurement, productivity analysis, ergonomics, footwear industry, optical tracking, industrial engineering, virtual simulation, time and motion study.

CAPTURA DE MOVIMIENTOS PARA EL ANÁLISIS DE OPERACIONES: CASO DE ESTUDIO SECTOR CALZADO

RESUMEN

El sector del calzado en Colombia está compuesto predominantemente por micro, pequeñas y medianas empresas (mipymes) que tienen en gran medida procesos manuales y presentan una baja tecnificación. Este estudio tiene como objetivo validar una metodología para el análisis de operaciones manuales a través de estudios de movimiento, en entornos reales de producción, utilizando sistemas ópticos de captura de movimiento (MoCap) integrados con simulaciones virtuales. Se analizó una tarea de ensamble manual en una empresa de calzado, utilizando cuatro cámaras infrarrojas y marcadores reflectivos ubicados en las muñecas y dedos índices de la trabajadora. Los datos de movimiento se procesaron en MATLAB para recrear virtualmente la operación e identificar el tipo y la frecuencia de los movimientos. Los resultados mostraron un total de 539 movimientos durante un ciclo de 90 segundos: 215 operaciones (39,9%), 35 transportes (6,5%) y 289 sostenimientos (53,6%). El tiempo promedio por operación productiva fue de 0,41 segundos, lo que arroja una productividad estimada de 146 operaciones por minute y 40 productos/hora.La simulación virtual evidenció una concentración de trayectorias de las manos dentro de la zona de alcance normal, indicando una disposición espacial eficiente. Sin embargo, la alta proporción de movimientos no productivos reveló oportunidades significativas de mejora en la estandarización de métodos y en el diseño ergonómico. La implementación de sistemas MoCap permitió una clasificación automatizada de los movimientos y el análisis de trayectorias sin segmentación manual, superando así la subjetividad y las limitaciones de la observación tradicional. A pesar de pérdidas menores de datos causadas por interferencias del entorno, el sistema demostró ser robusto y aplicable en un entorno industrial activo. Esta investigación demuestra la viabilidad de incorporar tecnología MoCap en estudios de tiempos y movimientos para contextos reales de manufactura, proporcionando información valiosa para el rediseño de procesos, la capacitación de operarios y la evaluación ergonómica.

Palabras clave: Captura de movimiento, ensamble manual, medición del trabajo, análisis de productividad, ergonomía, industria del calzado, seguimiento óptico, ingeniería industrial, simulación virtual, estudio de tiempos y movimientos.

INTRODUCTION

The footwear sector in Colombia is characterized by a strong presence of micro, small, and medium-sized enterprises (MSMEs) with manual manufacturing processes and low technological adoption. This production structure limits its competitiveness compared to countries like China, which leads the global footwear industry with over 12.6 billion pairs produced annually (approximately 60% of the global total), thanks to its installed capacity and low labor costs [1]. According to the Colombian Association of Footwear Industrialists (ACICAM) and the Ministry of Commerce, Industry and Tourism (MINCIT), the sector is composed of more than 28,000 formal entrepreneurs in the leather, footwear, and leather goods sectors in Colombia, who generate a significant impact on national employment and economic recovery [2], [3].

In recent years, Colombia's footwear industry has faced significant challenges in terms of production. According to Inexmoda and DANE data, footwear production in Colombia has shown a downward trend since 2022. The real production index from January to September 2024 fell by 3.3% compared to the same period in 2023, while sales declined 5.2% [4].

In absolute terms, market projections estimate that Colombia will reach an annual production of approximately 90 million pairs by 2025, a figure that has fluctuated from 90 to 100 million pairs in recent years [4], [5]. This figure is below the sector's installed capacity, which in previous years has exceeded 120 million pairs, but is currently operating below potential due to competition from imports and smuggling [4], as well as a shortage of skilled workers, which affects operational efficiency and productivity negatively [6].

In this context, industrial engineering and work studies emerge as fundamental pillars to improve the footwear industry's production process productivity . The study of work methods and times offers analytical tools to observe, record, and improve productive tasks. However, information collection on operations is still, in many cases, conducted manually through direct observation and a stopwatch, using pre-designed formats [7], which limits analysis precision, objectivity, and depth [8]. Although this is a low-cost methodology , it fails to capture the entirety of movements, time sequences, and ergonomic factors involved in an industrial operation, thus hindering the identification of bottlenecks, time waste, or inadequate postures.

To overcome these limitations, recent years have seen increased relevance of technological advancements in Industry 4.0 through motion capture (MoCap) systems, which allow for automated and precise recording of human body kinematics. These systems include optical (with or without markers), inertial (IMU), magnetic, and hybrid technologies [9]. Their application in industrial settings has enabled high-detail measurement of workers' movements in real time, identification of ergonomic risks, and objective productivity analysis [10], [11].

Recent studies have shown that MoCap systems—especially those enhanced with artificial intelligence—can achieve up to 99% accuracy in classifying work activities [10]. For example, in the construction sector, the implementation of inertial sensors enabled on-site productivity measurement with 96.47% accuracy, reducing the error rate from 24.65% to 3.53% [12]. In manufacturing, the use of markerless motion capture combined with augmented reality increased worker learning rates 22% and reduced work cycle duration up to 51% [13]. Moreover, systematic literature reviews indicate that the use of MoCap in industrial ergonomics has improved postural conditions up to 38% [9], [10].

Research also points out a common limitation in existing studies, as most experiments have been conducted in controlled environments or laboratories (learning factories), raising questions about the real-world applicability of these technologies in complex industrial settings with space constraints, visual occlusions, interferences, lighting variability, and actual work rhythms [9], [12], [14], [15]. Therefore, it is necessary to validate their feasibility and effectiveness in real industrial contexts.

In previous work [16], a first phase of method analysis was conducted using motion capture in a controlled environment. The study included an automated analysis of hand motion and timing using planar capture and virtual recreation of the operation. Results demonstrated the technical feasibility of the approach. However, its performance and applicability under real working conditions remain to be evaluated.

This study aims to validate a methodology to analyze industrial operations based on optical motion capture systems, applied to a workstation in a real Colombian footwear company . The goal is to analyze current operations using a MoCap system with infrared cameras, record complete sequences of movements, and recreate the task in a virtual environment. From this recreation, the aim is to analyze an operation's productivity and identify improvement opportunities difficult to detect through direct observation.

This study argues that the use of an optical motion capture system is viable and effective in real industrial settings—beyond the laboratory—enabling the recording of operational data with sufficient accuracy and robustness to enhance manual industrial operation analysis through time and motion studies. This will allow for the validation that such technologies can be implemented in real production conditions, with tangible benefits in productivity and ergonomics, as evidenced by studies reporting up to a 51% reduction in work cycle durations and up to a 38% improvement in postural conditions

[9], [10], [13], [17], [18]. The hypothesis is based on an expectation that this technology can overcome direct observation limitations and provide a more detailed efficient analysis of industrial work.

The document is structured as follows. Section 1 details the methodology employed, including the experimental design, technological system implemented, and application environment. Section 2 presents the results obtained in terms of motion recording, method analysis, and findings related to inefficiencies. Section 3 discusses identified benefits, limitations, and improvement opportunities . Finally, Section 4 summarizes the conclusions of the study and outlines future research directions.

It is worth noting that other studies have explored the integration of motion capture with digital twins to personalize ergonomics and optimize tasks in manual workstations [19], [20]. Additionally, automated ergonomic analysis tools have been proposed, based on posture estimation with monocular cameras and digital human modeling [15], [21]. Current industry trends point to combining motion capture with artificial intelligence algorithms to generate automatic ergonomic risk assessments, as shown in recent studies in flexible manufacturing environments [22], [23], [24]. These applications have demonstrated that incorporating inertial sensors and computer vision can facilitate rapid diagnoses of repetitive motions or forced postures [25], [26]. From a structural perspective, various reports indicate that strengthening technical capabilities through these tools can be decisive in closing productivity gaps in sectors such as Colombian footwear [27], [28], [29].

1. MATERIALS AND METHODS

A motion capture and analysis study was conducted on a manual operation in the real footwear sector using an optical motion capture system to record the operation. With the data obtained, the workstation was modeled in a virtual environment developed in Matlab. Through an algorithm designed in the Matrix Laboratory programming environment, it was possible to extract the basic movements of the recreated operation based on their sequence in an operational cycle. Finally, the methods used were analyzed, as well as workers' movements, speeds, and rhythm, to evaluate the efficiency of the method applied.

1.1 Process Description and Workstation Layout

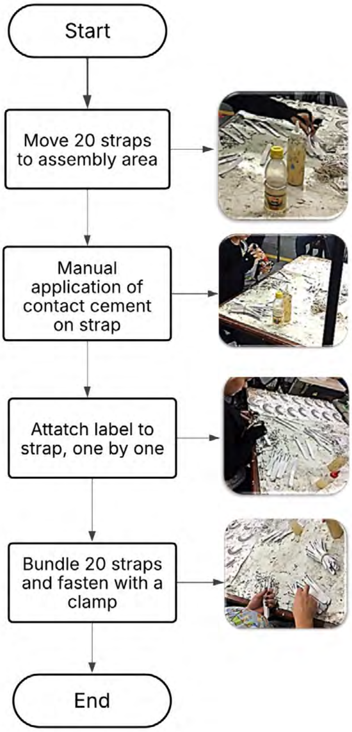
An experiment was conducted in a footwear company, specifically in a process called "placing labels on a size 27 children's shoe straps" (Table 1. Product Description). This piece secures shoes to children's feet. This product is manufactured manually by a single worker, following the operation method shown in *Figure 1.*

Table 1. Product description

Part	Material	Length (cm)	Width (cm	Height (cm)	Edge Profile	Image
Strap	White synthetic leather	16,1	2,0	0,2	Circular	
Label	Synthetic (with an embossed logo)	6,0	2,0	0,1	Straight	

Source: own elaboration

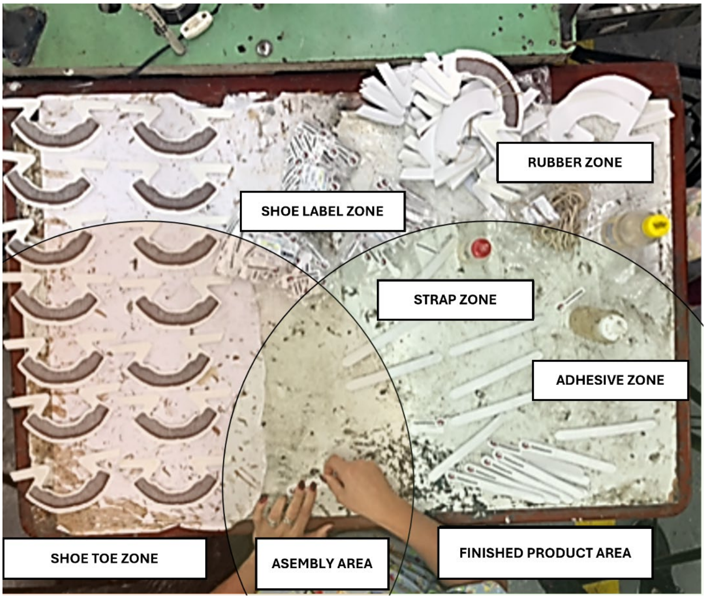
Figure 1. Shoe Strap Cementing Process Flowchart



Source: own elaboration

At the workstation, the parts and tools required for the operation are arranged; elements are detailed in *Figure 2*.

Figure 2. Workstation layout



Source: own elaboration

1.2 Motion Capture (MoCap)

An optical motion capture system was used, consisting of four OptiTrack V100:R2 infrared cameras (*Figure 3*), positioned at the lateral ends of the workstation. The captured data was processed using OptiTrack ARENA software. Additionally, tripods, a calibration level, a calibration triangle, a standard table (73 cm high, 73 cm wide, and 108 cm long), and a standard chair were used.

Figure 3 (A. Infrared camera, B. Test)

Source: own elaboration

To record the movements, four reflective markers were used—one on each wrist and one on each index finger (*Figure 4*). The worker wore a special suit with Velcro fasteners to properly secure the markers. The study was designed with a qualitative approach, aimed at identifying general movement patterns, physical strain areas , and ergonomic improvement opportunities in a real production environment.

The decision to use a limited number of markers was based on environmental conditions such as lighting, interferences, and available space, as well as the need to ensure a natural execution of the operation without disrupting the workflow or affecting workers' productivity. The amount of data collected was sufficient to meet the objectives of the study, particularly regarding observations of postures, movement trajectories, and critical points for improvement.

The system was calibrated, and data were captured in a one-hour session. During this time, workers' movements were recorded across different work cycles. The average duration of each cycle was 90 seconds per package of 20 finished straps—an appropriate time frame for short-cycle operation analyses .

Figure 4 Reflective markers

Source: own elaboration

1.3. Visualization of Movements in a Virtual Environment

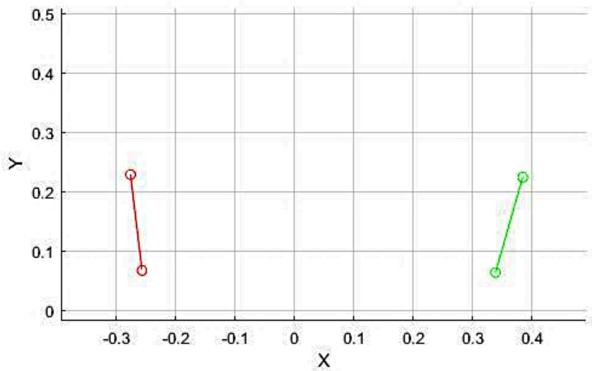
To simulate and analyze a real manual assembly process from the perspective of macro- and micro-motion studies and productivity, a simulation of the visual environment was developed using Matlab software. This tool allowed for workstation visualization , hand movement tracking through dynamic position graphs, posture change identification , detection of inactivity or holding periods, and complete operation procedure recreation .

The Matlab code reads the position and velocity data of each hand (*Figure 5*), which are contained in a coordinate matrix (*Table 2*) previously generated by the motion capture software.

The procedure followed to process the captured data includes the following stages:

1. Matlab code design to read , coordinate transform, and visualize hand and wrist movements.
2. Data storage in a CSV-formatted matrix consisting of *n* rows and 15 columns.
3. Simulation algorithm execution in Matlab, adjusting the actual dimensions of the workstation in a virtual environment.
4. Qualitative analysis of a simulated operation, focused on movement efficiency and on identifying potential ergonomic improvements.

Figure 5 Finger and wrist movement simulation in MatLab.
Green dots on the right hand. Red dots on the left hand.



Source: own elaboration

Table 2 Coordinate Matrix (n rows x 15 columns)

Time (s)	Right Hand (m)			Right Finger (m)			Left Hand (m)			Left Finger (m)			Right Speed (m/s)	Left Speed (m/s)
	X	Y	Z	X	Y	Z	X	Y	Z	X	Y	Z	x	x
.00	0.09725	0.23209	0.09473	0.08849	0.30317	0.14804	-0.33749	0.36962	0.09037	-0.27703	0.43295	0.04539	0.00116	0.00032
.01	0.09846	0.23178	0.09469	0.08965	0.30306	0.14793	-0.33786	0.37183	0.09113	-0.27736	0.43561	0.04731	0.00116	0.00032
.02	0.09982	0.23132	0.09463	0.09104	0.30271	0.14766	-0.33745	0.37339	0.09293	-0.27685	0.43785	0.05035	0.00139	0.00051
.03	0.10133	0.23084	0.09477	0.09275	0.30235	0.14784	-0.33659	0.37459	0.09529	-0.27628	0.43948	0.05314	0.00171	0.00057

Source: own elaboration

2. RESULTS

Manual operation motion recording of a real footwear sector case study , using an optical system composed of infrared cameras and motion capture markers, was successful. From this position, position and velocity data of both hands were obtained and processed in the programming software for later recreation and analysis. The following subsections present the results obtained regarding operation visualization and a kinematic analysis.

2.1. Virtual Environment Operation Visualization

Manual operation recreation in a virtual environment allowed for a detailed visualization of the trajectory of both hands of multiple work cycles. Unlike traditional analysis through direct observation, the algorithm developed in Matlab automated the segmentation of the operational cycle, identifying the start and end of each action without interrupting a recorded trajectory.

The system classified movements according to their functional nature (operations, transports, and holdings), based on hand coordinates and velocities along the X-axis. This classification was displayed in the Matlab console.

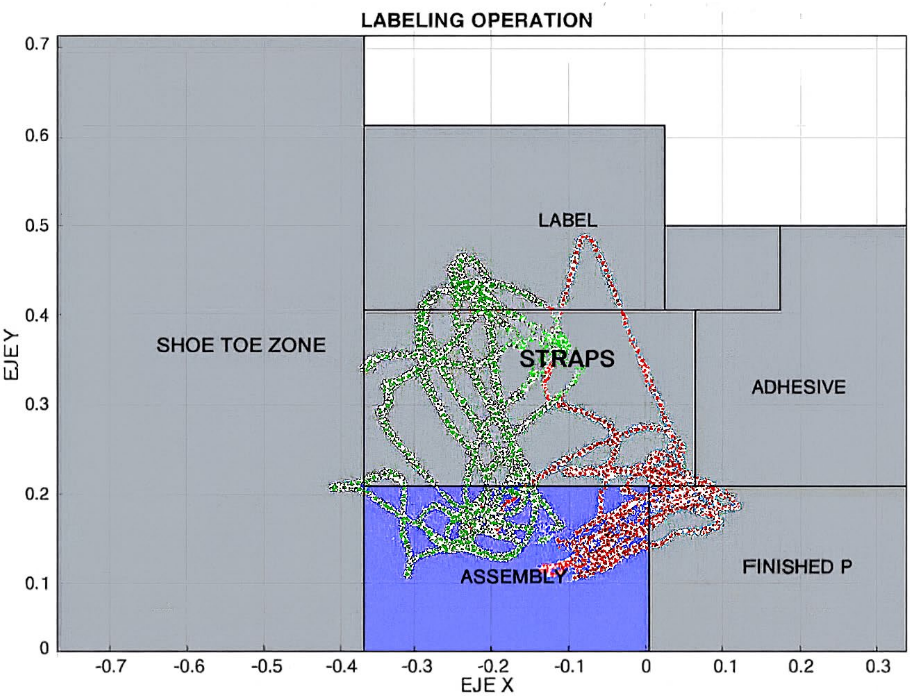
The temporal and spatial analysis of the captured data revealed a total of 539 movement instances over a 90.0-second interval, with an average frequency of 5.99 movements per second. A functional breakdown of these events is detailed in *Table 3*, with 39.9% corresponding to productive operations, 6.5% to transports, and 53.6% to unproductive operations, specifically holdings. It is important to note that activities that do not add value to an operation (i.e., no transformation occurs) are considered unproductive operations. The accumulated proportion of non-productive events (60.1%) indicates a need for intervention in method standardization and workstation redesign.

Table 3. Distribution of Movements by Type and Duration

Type of Movement	Frequency	Proportion (%)	Average time (s)
Operations	215	39,9 %	0,38
Transports	35	6,5 %	0,41
Holdings	289	53,6 %	0,32

Figure 6 shows the recreated workstation in the Matlab virtual environment, where the red dots represent the trajectory of the right hand and the green dots represent the trajectory of the left hand.

Figure 6 Hand Trajectories in XY Plane. Red track right hand – Green track left hand



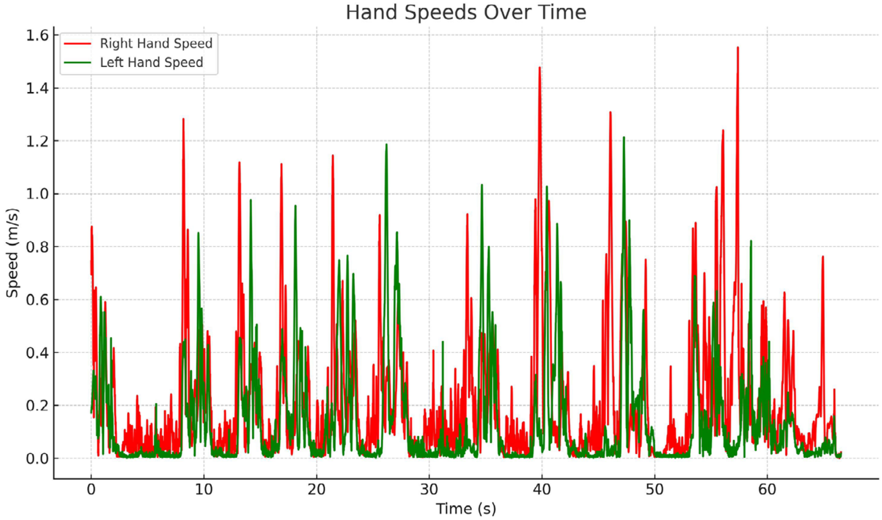
Source: own elaboration

2.2. Kinematic Analysis of Motion and Speeds

The kinematic analysis of both hand trajectories was performed using the data captured by the optical system, processed in Matlab to plot a spatial displacement on the XY plane. *Figure 6* illustrates the trajectories of the right hand and left hand, revealing a movement pattern concentrated in the lower area of the work plane. This behavior suggests an appropriate ergonomic arrangement of the manipulated elements, located in the normal reach zone, which reduces the need for forced extensions and improves gestural efficiency.

Moreover, the instantaneous velocities of both hands were calculated using time derivatives of the positions along the X, Y, and Z axes. *Figure 7* shows the temporal velocity evolution for each hand, allowing for the identification of phases of intense activity, functional pauses, and transitions between movements.

Figure 7. Hand Speeds over time



Source: own elaboration

The right hand showed greater dynamism and velocity peaks, suggesting that it performs most of the productive actions. In contrast, the left hand maintained more compact trajectories and lower speeds, indicating support or stabilization functions.

3. DISCUSSION AND ANALYSIS OF THE RESULTS

The results validate the effectiveness of optical motion capture systems as a tool for detailed analyses of manual operations in real industrial environments. Automatic segmentation based on algorithms overcomes direct observation limitations by eliminating subjectivity, enabling continuous recording, and reducing human error. In line with previous studies, the use of MoCap facilitates replicable objective diagnostics, even in real-world industrial settings.

3.1. Operation Visualization and Kinematic Analysis

From the hand trajectory results in the virtual environment, it can be observed that there is an overload of unproductive movements, mainly holdings, which could be optimized through better workstation layout and more efficient methods.

It was noted that the right hand exhibited higher speed peaks with abrupt accelerations associated with active tasks such as attaching the label and handling the adhesive. In contrast, the left hand showed more stable lower-magnitude speeds, indicating a support or passive positioning role during an operational cycle.

This analysis made it possible not only to identify highest activity areas but also to detect asynchronous movement patterns between both limbs, which may relate to asymmetric workload distribution. The information obtained provides a quantitative basis to propose improvements in task distribution between hands, tool redesign, and operator training based on more efficient movements. Furthermore, using trajectories and velocities as performance indicators allows for extending analyses beyond simple functional categorization, incorporating occupational biomechanics metrics and potential postural risk.

3.2. Productivity Analysis

Based on automatic movement classification , total cycle time analyzed was calculated to be 66.54 seconds, during which 215 productive operations were identified. This results in an average time of 0.41 seconds per operation, equal to a productivity rate of 146 operations per minute and 40 cycles per hour.

This outcome is consistent with a high-repetition cycle and low technological content but presents clear opportunities for improvement. If unnecessary holdings (which account for 53.6% of total movements) were reduced, productivity could significantly increase volume and ergonomic efficiency. Currently, 40 cycles/hour are performed, and each cycle produces a batch of 20 labeled straps (800 labeled straps/hour). If holding operations were eliminated, time would be reduced by 21% (71.1 sec/cycle), since average duration per cycle is 0.31 min (Table 3); production would increase to 50.6 cycles/hour, equal to 1,012 labeled straps/hour— a 26.5% increase in operational productivity.

3.3. MoCap Applicability and Limitations in Real Manufacturing Contexts

The use of motion capture systems for work method and time studies has proven to be a highly efficient tool, providing detailed, objective accurate operation analysis information . However, its implementation poses new challenges for industrial engineering professionals, who must develop additional skills in advanced technologies, algorithm programming, and validation of digitally obtained data.

Time and motion studies remain fundamental for the footwear sector, which continues to rely heavily on manual processes. The incorporation of this technology strengthens traditional studies, enabling more comprehensive, replicable, applicable diagnostics in real production settings. Its use can significantly contribute to productivity improvement and operational standardization. Nevertheless, two limitations were identified that should be considered in future studies:

- Spatial workstation variability : A changing layout of tools during the operation affected movement trajectory consistency . Standardizing aworkstation layout is necessary to achieve reliable comparisons.
- External interferences: Machine vibrations and personnel movement temporarily interrupted capture, highlighting the need for stricter environmental protocols.

As a recommendation for future research, it is proposed to integrate video recording as a complementary method to validate cycles, observe postures, and recover missing data, as well as the use of artificial intelligence technologies for automatic classification of movements (productive operations, transports, holdings, and waits).

4. CONCLUSIONS

A high proportion of unproductive movements (54%) was observed, representing a clear opportunity to improve productivity through method redesign and the implementation of ergonomic principles.

Higher trajectory concentration in the lower part of the work area indicates that the most frequently used elements were in the operator's normal reach zone. This layout reduced hand motion and, therefore, the time and effort required to do the operation, demonstrating efficiency in material workstation arrangement.

The limitations identified in the literature regarding traditional time and motion study methods are overcome implementing an optical motion capture system, which enables precise continuous data collection, eliminating issues associated with manual observation, such as subjectivity, visual fatigue, and information loss in short repetitive cycles.

The Matlab simulation, using algorithms that interpret hand position and velocity, enabled automatic movement type classification (productive vs. unproductive) without requiring manual segmentation. This represents a significant systematizing method analysis advance .

Despite using only four markers and experiencing some environmental interferences, the system successfully recorded sufficient data for functional and ergonomic operation analysis . This demonstrates that, with proper calibration and experimental design, it is feasible to apply motion capture technology in active industrial plants.

Future research could incorporate digital human modeling and AI algorithms to evaluate postural risks in real time and explore applicability in other highly manual industries.

Finally, the integration of motion capture and virtual simulation provides a solid quantitative foundation for decision-making in operation redesign, worker training, and method improvement—aligned with the principles of lean manufacturing and industrial ergonomics.

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