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COMPARING WHOLE-BODY VIBRATION EXPOSURE BETWEEN TWO EXCAVATORS IN AN ITALIAN QUARRY: A CASE STUDY

Guido ALFARO DEGAN[1], Andrea ANTONUCCI[2], Gianluca COLTRINARI[3], Sara INNOCENZI[4], Dario LIPPIELLO[5]*

[1]Università degli Studi Roma Tre, DIIEM, Italy, guido.alfarodegan@uniroma3.it
[2]Università degli Studi Roma Tre, DIIEM, Italy, andrea.antonucci@uniroma3.it
[3]Università degli Studi Roma Tre, DIIEM, Italy, gianluca.coltrinari@uniroma3.it
[4]Università degli Studi Roma Tre, DIIEM, Italy, sara.innocenzi@uniroma3.it
[5]Università degli Studi Roma Tre, DIIEM, Italy, dario.lippiello@uniroma3.it

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Abstract: *The purpose of this paper is to compare the levels of whole-body vibration (WBV) exposure to which operators are subjected when using conventional heavy equipment with internal combustion engines to hybrid heavy machines, which demonstrate potential advantages in terms of efficiency and sustainability. The study was carried out in a quarry using an experimental approach that analyzed conventional and hybrid heavy equipment during the same working phases in mining activities. The methodology involved direct vibration samples using triaxial accelerometers positioned uniformly on the operator's driving stations. The vibrations were analyzed in accordance with ISO 2631-1, focusing on intensity and frequency distribution. To minimize the influence of interference factors and ensure a straightforward comparison of the results, the entire measurement campaign was conducted under the same conditions, including vehicle and operator characteristics. Hybrid machines provide notable sustainability benefits, but the results show they produce higher vibration levels compared to conventional ones. This underscores the need to improve vibration control in hybrid machinery to ensure operator comfort and health while supporting their sustainability advantages.*
Keywords: *Whole-body vibration, Hybrid heavy equipment, Quarrying activities, Sustainability in mining, Professional exposure, Physical agents*

1. Introduction

Whole-body vibrations (WBV) pose a significant health risk to heavy machinery operators in the extractive sector, particularly those using dump trucks, excavators, and loaders. These vehicles, designed to operate in challenging environments with uneven surfaces, generate vibrations that can be amplified by several factors related to the machinery, the work environment, and the operators themselves [1]. Among vibration axes, the vertical (Z) axis records the highest acceleration, with particularly high peaks during specific operational phases such as return, transport, and material unloading, compared to loading and waiting phases [2, 3].

Scientific literature highlights the critical role of machinery age in WBV exposure [2]. Older vehicles tend to transmit higher vibrations due to the wear and tear of suspension systems and shock absorbers, thus compromising operator health and safety. In addition to mechanical factors, personal characteristics such as the operator's weight and anthropometric features influence the body's response to vibrations, making certain individuals more vulnerable. The location of vibration measurement on the operator's body also plays a crucial role in assessing exposure; for instance, measurements on cervical and lumbar vertebrae can yield different results [4].

The terrain on which heavy vehicles operate is another key factor; wet or slippery surfaces exacerbate vibrations [3]. Additionally, the vehicle's driving speed directly impacts WBV exposure: higher speeds lead to greater vibration intensity [5]. Therefore, integrated management of all these factors is essential to

[*] Corresponding author: Innocenzi Sara, eng. Ph.D stud., Università degli Studi Roma Tre, DIIEM, via Vito Volterra 62, Rome, Italy, sara.innocenzi@uniroma3.it

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mitigate WBV risks and ensure long-term operator safety. Despite extensive scientific research on WBV in the extractive sector, studies analyzing the impact of vibrations transmitted by hybrid heavy machinery remain limited. This topic is gaining relevance as stricter environmental regulations and the need to reduce carbon emissions become critical issues, both at the European [6] and national [7] levels. According to Dimension Market Research, the global market for electric and hybrid construction machinery is experiencing exponential growth, with a market value projected to reach $12.0 billion in 2023 and $76.1 billion by 2032, reflecting a CAGR of 22.8% [8]. Within this context, the hybrid excavator market stands out for its rapid expansion, valued at $0.7 billion in 2023 and forecasted to grow to $2.07 billion by 2031, with a CAGR of 12.8% from 2024 to 2031 [9]. This rising demand is supported by the adoption of more sustainable technologies, including improvements in WBV compared to traditional internal combustion engines, potentially leading to reduced WBV exposure and, consequently, a lower risk of musculoskeletal disorders.

However, transitioning to hybrid machinery in the extractive sector presents numerous technological and operational challenges. These vehicles must operate in extreme conditions (high temperatures, intense cold, humidity, and rough terrain), requiring hybrid engines to deliver reliability and durability. Fully electrifying heavy machinery introduces further complexities, as it demands high capacity batteries to meet the substantial energy needs of extraction sites. Energy density is a critical issue: diesel fuel has an energy density of approximately 12,000 Wh/kg, whereas lithium batteries provide only about 150 Wh/kg [10]. Consequently, achieving equivalent energy output would require significantly larger battery volumes compared to diesel, posing substantial logistical challenges for charging and maintenance in extraction operations.

Adopting hybrid machinery represents an initial step toward greater sustainability without necessitating significant changes to existing operational layouts. Such solutions could reduce carbon emissions, noise pollution, and operator exposure to WBV. However, uncertainties remain regarding the economic sustainability of hybrid and electric vehicle adoption [11], along with concerns about managing electrical energy in extraction environments, worker training requirements, and adjustments to safety procedures [12].

In this context, the present study aims to bridge this knowledge gap by analyzing and comparing whole-body vibrations generated by traditional and hybrid excavators. The research will provide empirical data to better understand the impact of new technologies on WBV risks in the extractive sector.

2. Materials and Methods

The study was carried out in a quarry near Rome, specializing in basalt extraction. Two different types of tracked excavators were used:

- Excavator 1: Liebherr 945, equipped with an internal combustion engine.
- Excavator 2: Komatsu Hybrid HB365LC/LC-3.

Table 1 provides the detailed technical specifications of both excavators.

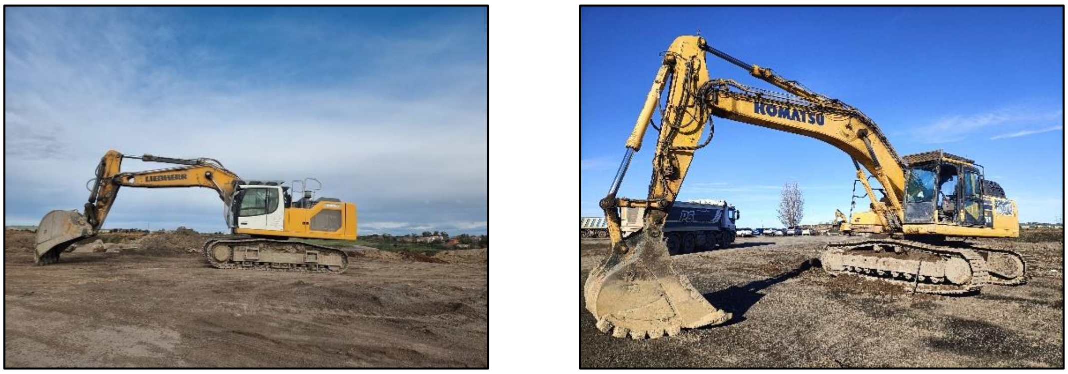

Fig.1. Excavator Liebherr 945 and Komatsu Hybrid HB365LC/LC-3

Table 1. Technical specifications of the excavators used

Excavator model	Year	Operating weight	Bucket capacity	Engine power
Liebherr 945	2021	48250 kg	3,00 m³	220 kW
Komatsu hybrid HB365LC	2016	36400 kg	2,66 m³	235 kW

The operator participating in the study has 20 years of experience operating excavators in extraction environments. He is 190 cm tall and weighs 130 kg.

An experimental approach was adopted to minimize the influence of external variables that could affect the results, to analyze the WBV generated by the two excavators. The following parameters were kept constant: the vibration measurement point, ground conditions, vehicle operating speed and the excavator's work phases. However, some variables could not be standardized, such as the age of the machines.

2.1. Data acquisition

Whole-body vibration (WBV) measurements were performed in accordance with the ISO 2631-1 standard. To ensure data representativeness, recordings were conducted for a duration sufficient to cover all operational phases of each excavator during the loading and unloading of material into the dumper. The common denominator for the analysis was the number of phases in each complete work cycle, which was consistent for both excavators. For both the Liebherr and Komatsu Hybrid excavators, each work cycle consisted of 10 distinct phases.

Each work cycle was defined as the complete process of loading the dumper and was divided into the following phases:

1. Loading phase: Collecting material with the bucket.
2. Rotation phase (loaded): Rotating the excavator's cabin and arm by 90° with a loaded bucket.
3. Unloading phase: Discharging the material into the dumper.
4. Rotation phase (unloaded): Rotating the excavator's cabin and arm by 90° with an empty bucket.

A total of six complete work cycles were analyzed for each excavator, resulting in the following breakdown of phases:

- Liebherr excavator: 60 loading phases, 60 rotation phases with a loaded bucket, 60 unloading phases, and 60 rotation phases with an empty bucket.
- Komatsu Hybrid excavator: 60 loading phases, 60 rotation phases with a loaded bucket, 60 unloading phases, and 60 rotation phases with an empty bucket.

For vibration measurements, a PCB tri-axial accelerometer, model 356B40, was used. It was positioned on the operator's seat and secured between the seat and the operator using adhesive tape, as shown in Figure 2. The orientation of the accelerometer axes was set as follows:

- Z Axis: Aligned with the operator's spine to record vertical vibrations.
- X Axis: Anterior-posterior direction to capture radial vibrations.
- Y Axis: Lateral direction to measure transversal vibrations.

The sensitivities of the accelerometers used are provided in Table 2.

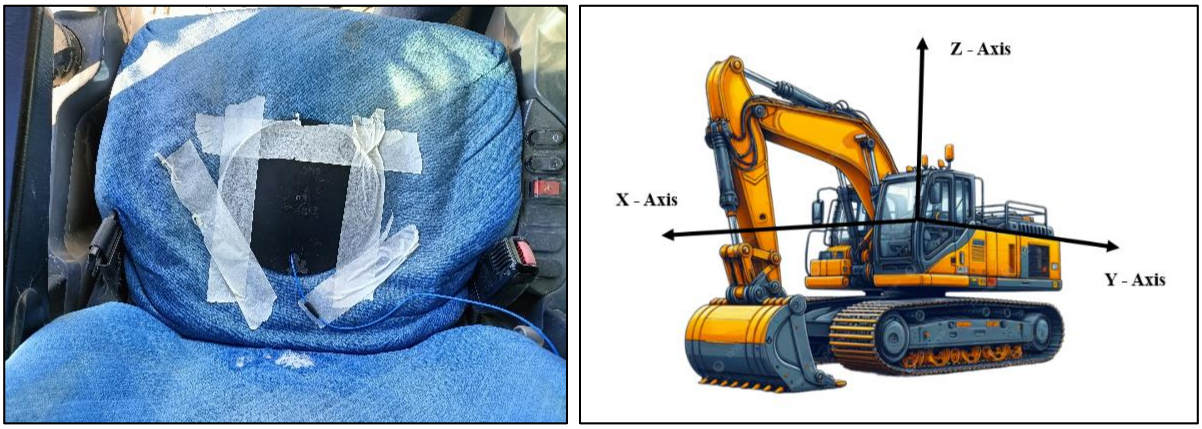

Fig.2. Mounting of the tri-axial accelerometer on the driver's seat

Table 2. Technical specifications of the accelerometer used

Accelerometer model	**Sensitivity X Axis**	**Sensitivity Y Axis**	**Sensitivity Z Axis**
Tri-axial PCB model 356B40	10,640 mV/(m·s^{-2})	10,600 mV/(m·s^{-2})	10,420 mV/(m·s^{-2})

The accelerometer connected to the Soundbook device recorded the signal, which was then processed using Samurai software.

2.2. Data analysis

The collected data were analyzed following the guidelines of ISO 2631-1 to ensure accuracy and consistency of the measurements. The measured vibrations were then processed with Samurai software, providing a comprehensive assessment of the operators' exposure to WBV vibrations throughout the entire operational cycle.

The acceleration values along the three analyzed axes were considered for each individual phase, using the appropriate measurement time required to complete each phase. The rotation phases typically lasted an average of 5 seconds, the unloading phase around 3 seconds, while the loading phase varied between 5 and 11 seconds depending on the material conditions. A resultant vector of the accelerations along the three axes was defined as follows:

$$a_{w,sum} = \sqrt{1{,}4 \cdot a_x^2 + 1{,}4 \cdot a_y^2 + 1 \cdot a_z^2} \quad (1)$$

where:

a_x: acceleration along the x-axis

a_y: acceleration along the y-axis

a_z: acceleration along the z-axis

Coefficient 1.4 is the weighting factor applied to the x and y axes, while coefficient 1.0 is the weighting factor for the vertical axis.

The root mean square (RMS) value of the acceleration over a given working time interval was calculated using the following formula:

$$a_{w,rms} = \sqrt{\frac{1}{N} \cdot \sum_{i=1}^{N} a[i]_w^2} \quad (2)$$

where *N* represents the total number of samples.

3. Results

The analysis of acceleration values along the three axes revealed that the Y-axis was the least solicited for both excavators. Among the different work phases, the loading phase was found to generate the highest vibration levels. Specifically, the average acceleration values recorded during this phase were 1.17 m/s² for the Liebherr excavator and 1.70 m/s² for the Komatsu Hybrid excavator. The least solicited phase for both types investigated is the material unloading phase, with an average effective acceleration of 0.31 m/s² for the Liebherr excavator and 0.48 m/s² for the Komatsu Hybrid excavator.

Below are summary tables showing the effective acceleration values measured across the four different phases, referring to the effective value of the acceleration vector. The tables also include the corresponding standard deviation values, variance, maximum, and minimum recorded values for each phase, with a number of samples equal to 60 for the Liebherr 945 excavator and 60 for the Komatsu hybrid excavator.

Table 3. Summary table of values during the material loading phase

Working phase		**Liebherr 945**	**Komatsu hybrid HB365LC**
Material loading phase	Mean	1,17 m/s^2	1,70 m/s^2
	Standard Deviation	0,45	0,44
	Variance	0,20	0,19
	Maximum	2,45 m/s2	2,89 m/s2
	Minimum	0,41 m/s2	0,59 m/s2

Table 4. Summary table of values during the rotation phase with the bucket loaded with material

Working phase		**Liebherr 945**	**Komatsu hybrid HB365LC**
Rotation with loaded bucket	Mean	0,62 m/s^2	0,94 m/s^2
	Standard Deviation	0,30	0,33
	Variance	0,09	0,11
	Maximum	1,44 m/s2	1,73 m/s2
	Minimum	0,19 m/s2	0,44 m/s2

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Table 5. Summary table of values during the material unloading phase

Working phase		**Liebherr 945**	**Komatsu hybrid HB365LC**
Material unloading phase	Mean	0,31 m/s^2	0,48 m/s^2
	Standard Deviation	0,12	0,18
	Variance	0,01	0,03
	Maximum	0,64 m/s2	0,90 m/s2
	Minimum	0,10 m/s2	0,16 m/s2

Table 6. Summary table of values during the rotation phase with empty bucket

Working phase		**Liebherr 945**	**Komatsu hybrid HB365LC**
Rotation with empty bucket	Mean	0,42 m/s^2	0,55 m/s^2
	Standard Deviation	0,11	0,16
	Variance	0,01	0,03
	Maximum	0,71 m/s2	0,99 m/s2
	Minimum	0,21 m/s2	0,26 m/s2

The following graphs illustrate the acceleration trends along the three axes for the six complete work cycles, for the two different types of excavators. The acceleration along the x-axis is represented in blue, along the y-axis in red, and along the z-axis in green.

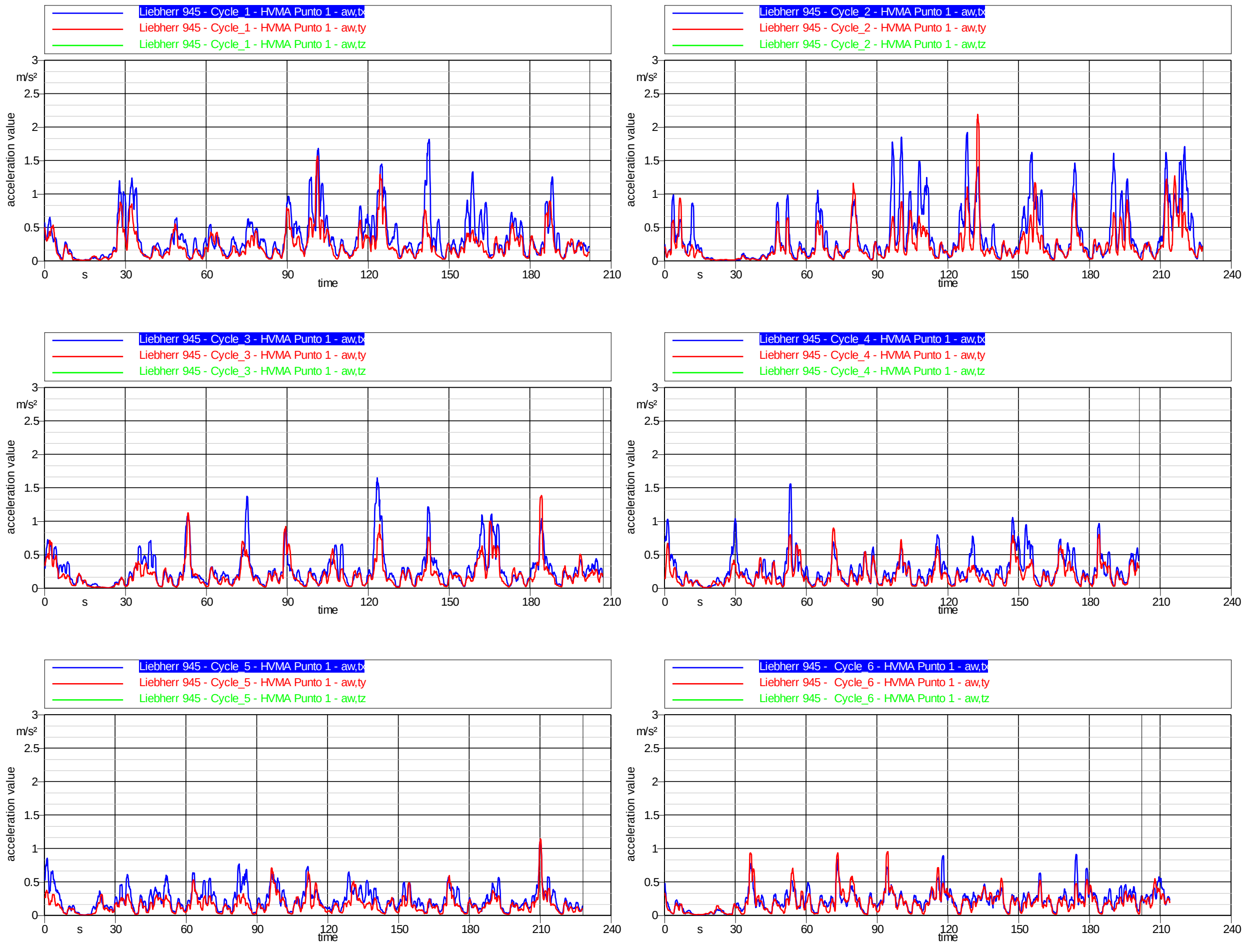

Fig.3. Trend of vibrations along the 3 axes for the 6 work cycles - Liebherr excavator

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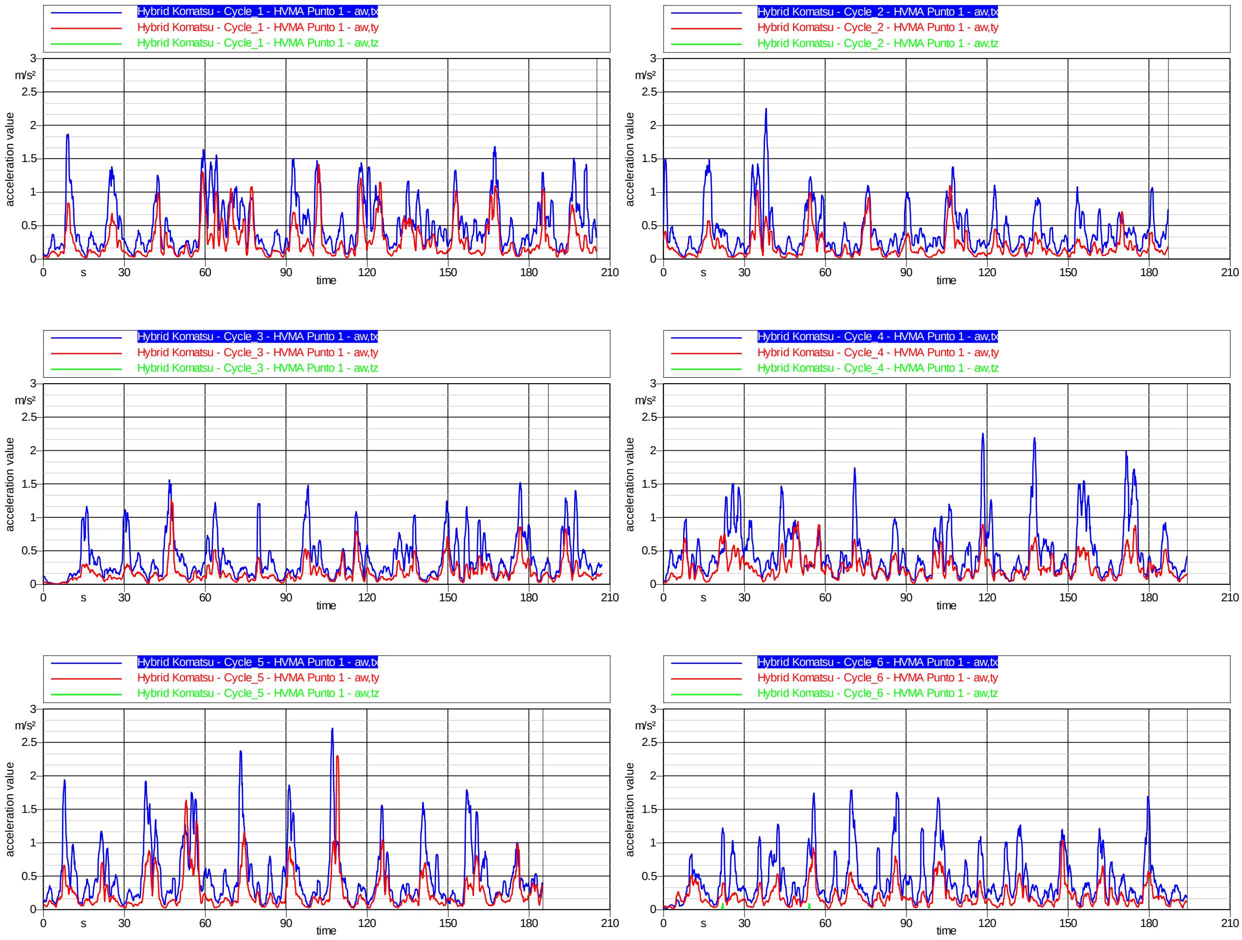

Fig.4. Trend of vibrations along the 3 axes for the 6 work cycles - Hybrid Komatsu excavator

Below is a sample sub-cycle for each analyzed excavator, highlighting the operational phases of material loading, rotation with the loaded bucket, material unloading, and rotation with the empty bucket. The sub-cycles were extracted from cycle 2 for the Liebherr 945 excavator and from cycle 3 for the Komatsu hybrid excavator. In both cases, it is observed that during the loading phase, which is the most stressed in terms of vibrations transmitted to the operator, the axes most affected are the z-axis and the x-axis.

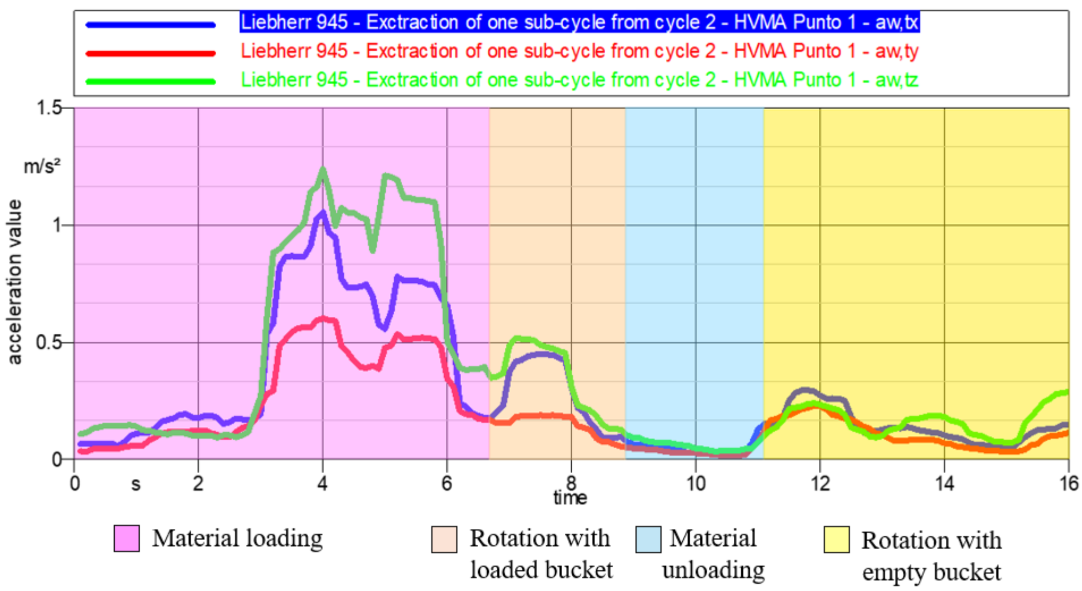

Fig.5. Liebherr 945 Excavator - Sample Sub-cycle

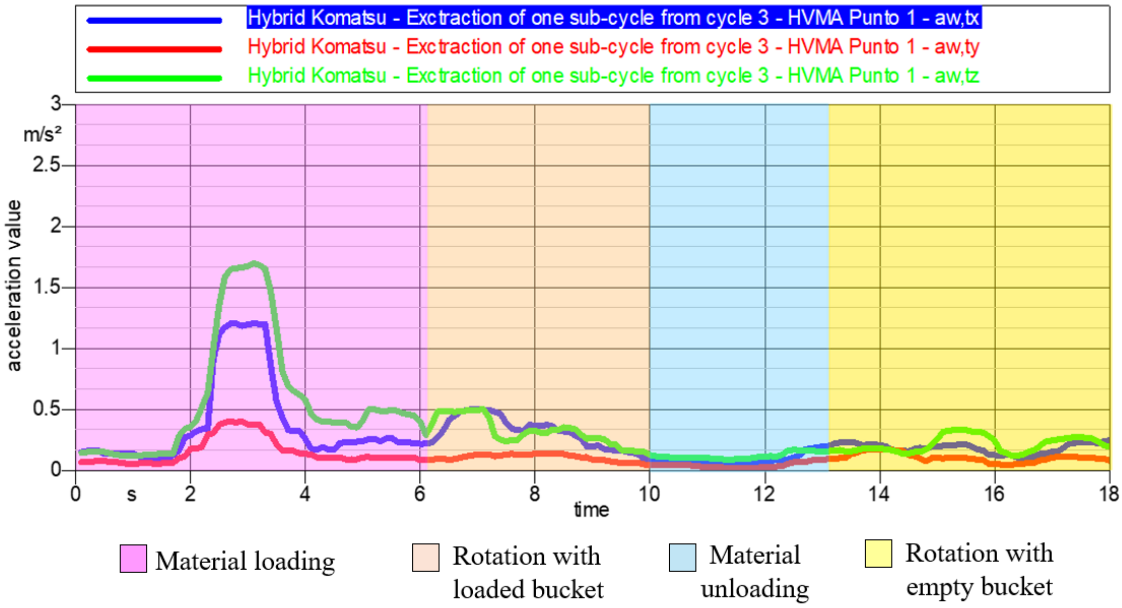

Fig.6. Hybrid Komatsu Excavator - Sample Sub-cycle

Below are the scatter plots of the measurements taken for each individual work phase, considering the acceleration vector. These plots directly compare the values obtained for the two excavators and examine the correlation between them.

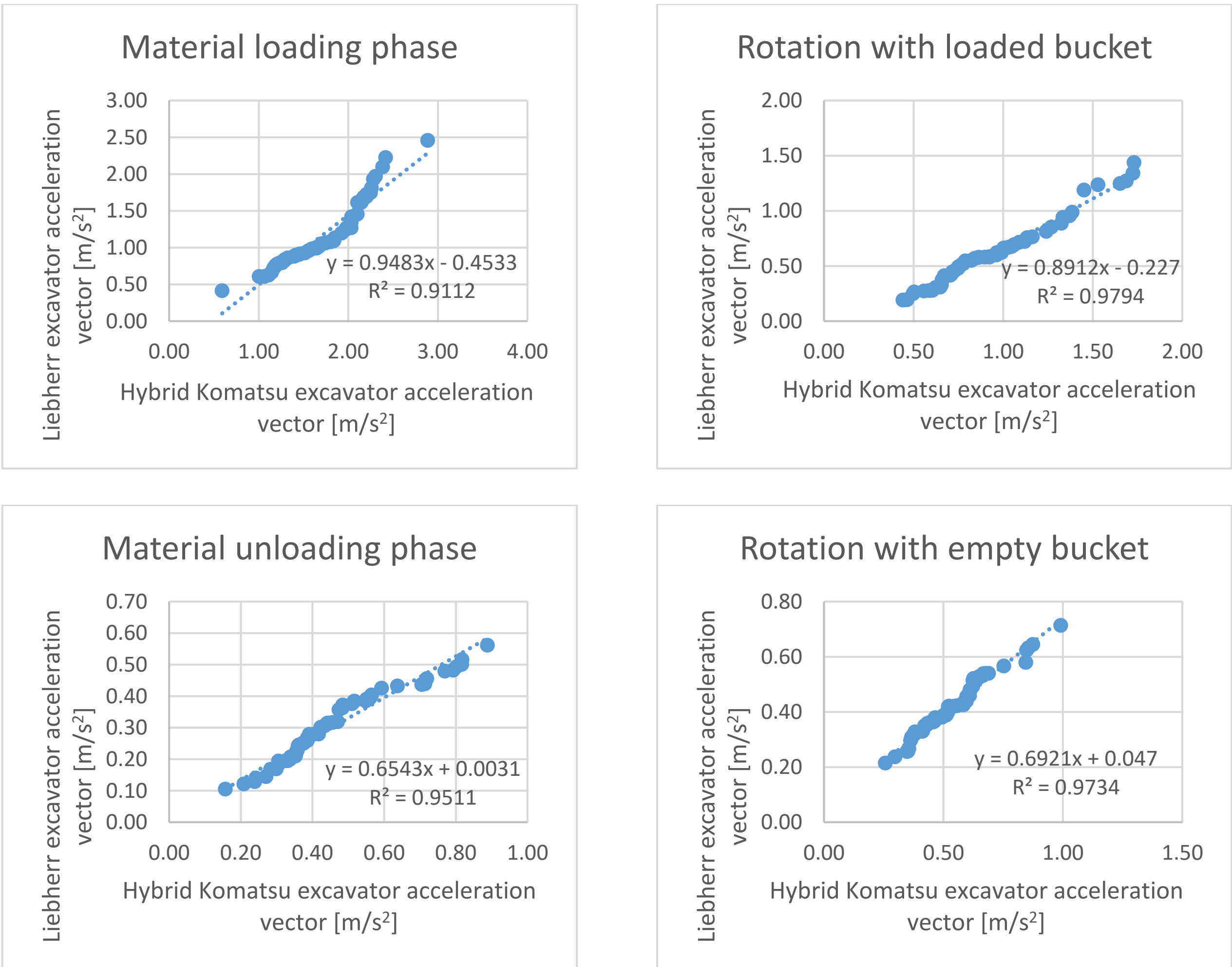

Fig.7. Correlation of acceleration vector values recorded for each work phase of both excavators

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4. Discussion

The results obtained for the two excavators indicate that, despite maintaining consistent operating conditions (same work phases, same material extracted with unchanged density, and the same operator, ensuring uniformity in both operator experience and anthropometric parameters), significant acceleration vector peaks were recorded during specific loading phases. From the graphs of cycles 5 and 6 of the Liebherr excavator, it is visually evident that the peaks recorded are significantly lower compared to those observed in the initial work cycles. This phenomenon can be attributed to the fact that, in those cases, the excavator handled softer material, whereas the higher peaks were observed during the loading of basalt boulders.

A constant observation across the measurements for both excavators is that workers are exposed to higher vibration levels during the loading phase, identified as the most critical phase. In contrast, vibrations are significantly lower during the unloading phase, in which the excavator primarily moves the bucket to release the material.

The higher vibrations transmitted by the hybrid excavator compared to the traditional model could be attributed to several factors. One notable aspect might be the difference in technology and design between the two machines: the hybrid excavator, manufactured in 2016, may not benefit from the same advancements in vibration isolation and suspension system optimization present in the more recent traditional model (2021). Additionally, the presence of hybrid components, such as the electric motor and transmission system, could influence the distribution of vibrations, making it more challenging to fully control the forces. Another contributing factor could be the difference in weight and load distribution between the two models, which may affect their dynamic behavior during operation.

5. Conclusion

A measurement campaign was conducted in a basalt quarry near Rome, with the aim of analyzing the vibrations transmitted to the whole body by two different excavator models: a Liebherr 945 and a hybrid Komatsu HB365LC. The comparison was direct, keeping constant both the type of material handled and the operator using the excavators, thus ensuring similar anthropometric characteristics and experience.

To carry out the work, 6 dump truck loading cycles were analyzed for each excavator, subdivided into 10 subphases per cycle, resulting in 60 acceleration data points for each of the following phases: loading, rotation with bucket loaded, unloading, and rotation with bucket unloaded.

The results revealed that the phase which exposes the operator to the highest levels of vibration is the loading phase for both excavators, with an average acceleration vector value of 1.17 m/s^2 for the Liebherr and 1.70 m/s^2 for the hybrid excavator. In contrast, the least critical phase turned out to be the unloading phase, during which vibrations were significantly lower, with an average acceleration vector value of 0.31 m/s^2 for the Liebherr 945 excavator and 0.48 m/s^2 for the Komatsu hybrid HB365LC.

However, drawing more robust and representative conclusions requires a broader dataset that accounts for a wider range of operating conditions, material types, and hybrid excavator models. Expanding the measurement sample would strengthen the validity of the findings and provide a more comprehensive understanding of the factors influencing vibration exposure.

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