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Advancing Timber for the Future Built Environment

ASSESSING VIBRATIONAL PERFORMANCE IN DIFFERENT TIMBER FLOOR CONFIGURATIONS: AN EXPERIMENTAL STUDY

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ABSTRACT: The construction of timber structures offers a significant advantage in reducing the carbon footprint associated with building activities. However, to fully realize this benefit, it is essential to enable the construction of large and tall timber buildings. Achieving this goal presents certain engineering challenges, particularly concerning human-induced vibrations on timber floors, which are more pronounced in large-span spaces. The lightweight and lower stiffness of timber floors result in vibrating frequencies that fall within the range easily perceptible by humans. Therefore, designing timber floors with optimal vibrational characteristics, such as predominant frequency and damping, is crucial for ensuring comfort and constructability. This research investigates these challenges through a series of experiments on six timber floors, each constructed with three different structural combinations and two varying finishing conditions. The experimental procedures included static loading and human walking tests. This paper presents the preliminary results from these experiments, offering insights into the vibrational behavior of timber floors and their implications for future construction practices.

KEYWORDS: timber floor, vibration control, human induced vibrations, experiments

1 – INTRODUCTION

Growing emphasis on sustainability in the construction industry has accelerated the use of timber as a structural material. Favorable carbon footprint of timber, along with rapid construction possibilities and aesthetic qualities, make it an attractive option for modern buildings. However, its lightweight and flexible nature introduces engineering challenges, particularly related to human-induced vibrations in floor systems. These vibrations, if not properly controlled, can lead to user discomfort and serviceability problems, especially in office spaces and long-span applications where walking or jumping causes dynamic floor responses.

Recent developments in timber floor engineering have proposed several strategies to improve vibration performance, such as increasing section depth, adding composite topping layers, optimizing joist spacing, or incorporating passive damping systems. Among these, composite action via screed or topping layers remains the most practical and widely adopted method, especially in large-span timber floor applications. However, the effectiveness of such measures can vary depending on the structural system used, and clear guidance on their performance under real-world loads remains limited.

Eurocode 5 [1] and ISO 10137[2] provide general criteria for floor design in terms of deflection, frequency, and acceleration limits under service conditions. For instance,

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Eurocode 5 recommends that the fundamental frequency of the floor under dead load should exceed 8 Hz to avoid resonance with human activities. Meanwhile, ISO 10137 emphasizes comfort-based thresholds for RMS accelerations during walking or rhythmic movement. Yet, these documents leave significant flexibility in terms of how different structural systems should be modeled or verified experimentally, highlighting the importance of calibrated full-scale testing.

Recent research has addressed the dynamic behavior of timber floors through both experimental and numerical approaches. Chocholaty et al. [3], for example, evaluated vibroacoustic behavior of hybrid steel–timber floors using full-scale experiments and FE model calibration techniques. Their findings suggest that although hybrid systems show promising performance, additional design measures are often necessary to meet vibration comfort thresholds. Similarly, Aloisio et al. [4] reviewed methods for assessing vibrations in mass timber and hybrid floors, emphasizing inconsistencies between simplified analytical models and experimental modal analyses. These discrepancies may lead to either overly conservative or unsafe designs.

Hassan and Girhammar [5] showed that glued joints significantly improve natural frequencies and reduce deflections compared to nailed or screwed connections, meeting criteria set out in Eurocode 5 [1]. A long-term perspective is offered by Zhang et al. [6], who reviewed over 200 years of research on deflection criteria for timber floor vibrations. Their findings underline the need for updated design standards that better reflect modern expectations of comfort and evolving floor systems.

Despite the growing body of literature on vibrational performance of timber floors, comparative full-scale experiments on a range of common timber floor types under consistent testing protocols remain limited. Existing studies often focus on a single floor system or rely on numerical simulations with limited experimental calibration. This research addresses this gap by conducting a systematic experimental investigation on six full-scale timber floor systems, constructed using three structural configurations; Open-Web Joists, Cross-Laminated Timber (CLT), and Rib Panels, with and without a anhydrite gypsum-based topping.

Anhydrite gypsum was used as the topping material in the experiments due to its lower embodied carbon and simpler application process compared to traditional concrete. Unlike cement-based toppings, it requires less energy for production and installation, making it a more environmentally sustainable choice for improving the stiffness and vibration performance of timber floors.

Through a series of quasi-static and dynamic tests, including 1kN point loads and walking excitation, the study provides detailed insights into stiffness and vibration response.

2 – TEST SETUP

Prior to testing, the topping layers were applied directly onto the timber surfaces using an adhesive primer, and allowed to cure for a period of four weeks in controlled indoor conditions. This ensured adequate bonding and full development of stiffness contribution from the topping. All timber elements were stored and conditioned in the lab space for at least two weeks before construction to minimize variability due to moisture content. Edge conditions were kept free (non-clamped) to simulate realistic simply supported behavior. No acoustic insulation or resilient layers were used between the structural elements and the toppings, to allow direct evaluation of composite mechanical performance.

The test setup includes six floor systems placed on supports at the two ends (Figure 1). Three flooring systems were tested: Open-Web Joist, Cross-Laminated Timber (CLT), and Rib Panel configurations. Each configuration was constructed twice, one without any topping and one with a topping consisting of anhydrite and gypsum (Figure 2). Floors with and without topping had identical dimensions, which are given in Table 1.

The open-web joist system was built using four joists made of 46×146 mm flanges of C24 grade timber. Strongbacks of 38×120 mm, grade C24, were applied at quarters and at the mid-span. Strongbacks increase the transverse stiffness of the floor in the direction perpendicular to the joists, enhancing rotational and two-way stiffness. This increase in stiffness significantly improves the vibrational performance of the floor, as shown in the upcoming sections. A 22 mm oriented strand board (OSB) was used at the top, with an assumed modulus of elasticity of 3.5 GPa [7]. The OSB panels were screwed to the top flanges of the joists using 5×60 mm wood screws at approximately 30 cm spacing.

The CLT floors were made of 240 mm thick panels, composed of seven layers, four of which had grains parallel to the longitudinal direction. The layer thicknesses were as follows (layers with perpendicular grain orientation shown in curly brackets): 40 mm – {20} – 40 – {40} – 40 – {20} – 40. The CLT panels were Derix L-

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240/7s, and their properties were defined in the European Technical Assessment for Derix CLT [8].

The rib panel floor system was composed of four vertical laminated veneer lumber (LVL) ribs, each 51 mm thick. The top and bottom plates were made of 31 mm thick LVL. The ribs and plates were glued together during production. The LVL members were manufactured from European spruce in compliance with EN 14374 [9].

Table 1: Dimensions of the tested floors (dimensions in meters)

Floor Type	L	Lc	D	a	b
Open-Web Joist	6.62	5.78	1.22	0.22	0.20
CLT	6.42	5.86	1.20	0.07	0.21
Rib Panel	6.42	5.84	1.20	0.08	0.21

Sensors used in this study included single-axis force balance accelerometers and linear potentiometers. The accelerometer, with a flat frequency response from DC to 200 Hz, was selected for its ability to precisely detect the natural frequencies of the floor systems. It was paired with a simultaneously sampled 24-bit Analog-to-Digital Converter (ADC) to ensure high-resolution, low-noise data acquisition. Accelerometers were mounted at three locations, at two quarters and the mid-span, to capture dynamic responses across the floor systems. Linear potentiometers, used to measure vertical deflections, were placed at the mid-point on both sides of each floor to assess displacement and any torsional behavior. Instrument positions are shown in Figure 1.

3 – CONDUCTED TESTS

3.1 STATIC (1kN) LOADING TEST

To assess the stiffness performance of each floor type, static load tests were first conducted by applying a 1 kN point load at three positions along the floor span: L/4 (west quarter), L/2 (mid-span), and 3L/4 (east quarter). The load was distributed over a 50 cm wide area centered on the floor in both directions to approximate a point load. Linear potentiometers were placed at the center of the span, on both sides of each floor system, to measure vertical displacements. Each test began from an unloaded state, with steel blocks incrementally placed until the total load reached 1 kN. Figure 1 illustrates the test setup, including placement of the accelerometers, potentiometers, and static load application.

Displacements were calculated using the averaged values during a silent period immediately following load placement, after filtering and detrending the data. A third-order Butterworth low-pass filter with a 5 Hz cutoff frequency was applied to eliminate high-frequency noise while preserving the relevant deformation signals.

Measured displacements were compared to those predicted during the design phase. Figure 3 presents the mid-span deflections under 1 kN applied at the center.

Figure 3 compares the measured mid-point deflections of three timber floor systems, open-web joist, CLT, and ribbed panel, with the design deflections calculated based on Eurocode 5 [1] for a 1 kN point load at mid-span. Notably, all the design calculations assumed the presence of a topping layer, which is consistent with practical use. The measured deflections for the topped floors (blue circles) are in close agreement with the Eurocode-based design values (black crosses), especially for the ribbed panel and CLT floors, confirming the accuracy and reliability of the design assumptions. The open-web joist floor showed a slightly lower deflection than predicted, likely due to conservative assumptions in stiffness contributions during design. Floors without topping (red triangles), tested only for comparative insight, consistently exhibited higher deflections, underlining the importance of composite action from the topping in achieving the intended stiffness.

All results remained within the expected design limits, confirming the validity of the design assumptions. An important observation is that while the weight of the topping was considered in the design calculations, its contribution to overall floor stiffness was not. As a result, actual displacements were generally lower than predicted, especially for the open-web joist floor.

To further quantify the impact of topping, flexural stiffness (EI) values were calculated for each floor using the closed-form expression for mid-span deflection of a simply supported beam under a central point load, as shown in (1):

$$\delta_{max} = PL^3 / 48EI \qquad (1)$$

where P is the applied load, L is the clear span length, and EI is the flexural rigidity.

Topping increased stiffness substantially while also increasing weight, particularly in the CLT and rib panel systems. This stiffness increase is inferred from the mid-point deflections measured at the floor with and without topping, assuming the floors remained elastic during and after the experiments. According to this, open-web joist,

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CLT and rib panel floors had 462%, 122% and 214% increase in weight, while the stiffness increase was 22%, 126% and 159%. The open-web joist floors had the highest weight increase with the lowest stiffness increase, as they were very light weight but stiff at the same time before adding the topping. The CLT floors had smilar increase both in weight and stiffness.

3.2 WALKING TESTS

Dynamic performance of the floor systems was assessed through walking tests conducted by four individuals, each walking twice over the floor in a predefined path. The participants' weights were 75 kg, 104 kg, 80 kg, and 70 kg. The same footwear was used by all participants to ensure consistency. The walking path, shown in Figure 1, was designed to simulate realistic occupancy-induced vibrations. The walks were executed consecutively, with minimal pause between the two passes per person.

Accelerometers and potentiometers recorded both displacement and acceleration responses at key points along the floors. The shaded area indicates measurement uncertainty, while the solid line shows filtered data. The path began at the southern edge of the floor, passing over the mid-span and returning from the opposite side. Peak displacements occurred near mid-span, where dynamic effects were most pronounced.

Due to asymmetry in human gait and inherent torsional behavior in one-way slab systems, responses varied slightly between the two potentiometers. Among the three floor types, the open-web joist exhibited the highest torsional response, followed by the rib panel, with CLT performing the best in minimizing torsion.

Maximum displacement and acceleration results are summarized in Figures 3 and 4. Box plots reveal higher response variability for floors without topping, especially in the open-web joist system. Variability across participants and repeated tests was closely linked to the magnitude of displacements, indicating a strong correlation between stiffness and dynamic consistency.

The results also highlight a notable trend: the heaviest participant generated the highest dynamic response on all floor types except the rib panel with topping—the stiffest floor in the series. This suggests that the interaction between occupant mass and floor stiffness plays a dominant role in governing vibration amplitudes.

Root Mean Square (RMS) acceleration, equation of which is shown in (2), was used to quantify vibration levels, consistent with ISO 2631 guidelines for evaluating human comfort [9]. RMS was calculated over a 1-second moving time window. RMS is particularly useful for assessing the vibrational impact of transient and irregular loads, such as walking, and remains the principal design criterion in several international standards.

$$RMS = \sqrt{\frac{1}{T}\int_0^T x^2(t)dt} \qquad (2)$$

where x(t) is the time-varying signal, T is the total duration, and RMS represents the root mean square value, computed as the square root of the mean of the squared signal over time.

Floors were designed in accordance with Eurocode 5 and its National Annex, which require that the fundamental frequency under dead load exceeds 8 Hz, and that mid-span deflections under a 1 kN point load remain within specified limits [10]. Measured values indicate that all floors satisfy these criteria, with topping yielding considerable improvements in both stiffness and vibration performance.

A comparative analysis across the floor types reveals that the rib panel with topping consistently performed best in terms of both stiffness and dynamic comfort, followed closely by the CLT system. The open-web joist system, although very efficient in terms of material usage and lightweight design, showed more variation in dynamic response, likely due to its lower inherent damping and more flexible transverse behavior. These differences emphasize that not only the vertical stiffness but also torsional and composite behavior of floor systems play a key role in dynamic performance. Furthermore, heavier participants generally induced higher RMS responses on more flexible floors, suggesting a potential need for user-weight-dependent design checks in certain applications.

The RMS vibration measurements obtained from various timber floor systems offer insights into their dynamic performance under walking excitation, evaluated in light of the comfort criteria outlined in Eurocode 5 [1], and ISO 10137 [10]. While the open-web joist and CLT systems without topping were included primarily for comparative analysis, their results highlight the influence of added mass and stiffness in vibration mitigation. As expected, the versions without topping exhibited higher RMS values due to their lighter configurations, which are not typically used in real-world applications. The inclusion of a topping significantly reduced the RMS response in both systems, demonstrating the critical role of composite action in improving serviceability and aligning with comfort thresholds typically set around 8–9 mm/s² for residential or office use.

Among the tested configurations, floors with concrete topping, including the open-web joist, CLT, and ribbed panel systems, consistently achieved RMS values within or below comfort limits across different walking scenarios. This indicates that, when designed with appropriate composite sections, all floor types can offer satisfactory vibration performance. The tested systems with topping showed particularly stable and low RMS responses, reinforcing their suitability for environments with higher comfort expectations. These findings support current design practices encouraged by Eurocode 5, where the use of topping and increased stiffness is essential to control floor vibrations and ensure occupant comfort.

While the tested floor systems with anhydrite and gypsum-based toppings demonstrated strong performance in terms of vibration serviceability, they also offer a more environmentally favorable option compared to traditional concrete toppings, due to their lower embodied carbon and easier application. Nevertheless, to further align with circular construction principles, it remains important to explore fully bio-based alternatives derived from renewable or recycled sources. Composites made from materials such as hemp-lime, wood fiber, or other plant-based binders show potential for providing the required mass and stiffness while further reducing environmental impact. Future research should investigate the mechanical and dynamic behavior of these sustainable topping solutions to ensure they meet both structural and comfort performance standards in timber floor systems.

In addition to bio-based composites, another promising approach involves the use of granular materials as a topping layer. These materials can provide the necessary mass to lower vibration amplitudes, while also introducing damping through inter-particle friction. The energy dissipation mechanisms inherent in granular systems—such as sliding, rolling, and collision between particles—can be highly effective in reducing floor vibrations, particularly under dynamic loads like walking [11, 12]. Moreover, depending on the choice of material, such systems can be designed to be reusable, recyclable, and adaptable, contributing to the goals of circular construction. Research into the optimal grain size distribution, confinement techniques, and interface behavior with timber substrates will be essential to unlock the full potential of this approach for vibration control in lightweight floor systems.

4 – CONCLUSIONS AND FUTURE WORK

This study presented a systematic experimental investigation into the vibrational performance of six full-scale timber floor systems, built using open-web joists, cross-laminated timber (CLT), and ribbed panels, both with and without topping. The tests included static loading, dynamic walking excitations, and RMS acceleration analysis. Results show that all floors constructed with a topping layer met the design requirements specified in Eurocode 5 for stiffness and vibration performance. Measured mid-span deflections under static 1 kN point loads closely matched predicted values, confirming the validity of the design assumptions. Floors without topping, tested only for comparison, consistently showed higher deflections and vibration responses due to reduced mass and stiffness, underlining the critical role of the topping in ensuring serviceability.

Dynamic testing under human walking excitation further confirmed that floors with topping performed significantly better in terms of comfort, showing lower RMS acceleration values that generally fall within ISO 10137 comfort thresholds for building floors. While all topped systems, open-web joist, CLT, and ribbed panel, demonstrated acceptable performance, the ribbed panel system showed the most consistent behavior across participants, indicating higher torsional and flexural stiffness. The topping layer enhanced both the vibrational and stiffness properties of the systems, making them suitable for use in large-span or high-occupancy timber structures.

Beyond performance, the study also highlights the opportunity to further enhance the sustainability of topping materials. The anhydrite and gypsum-based toppings used in this study not only contributed significantly to structural performance, but also present a more environmentally conscious choice compared to traditional concrete, due to their lower embodied carbon and energy-efficient production. However, as they are not fully bio-based or circular, future work should focus on the development and testing of topping materials made from renewable resources, such as hemp-lime, wood-fiber composites, or other plant-based binders. These emerging alternatives may offer comparable structural benefits while pushing the boundaries of sustainability in timber floor construction.

Additionally, the potential use of granular materials as a topping layer presents a novel strategy, offering the dual benefits of added mass and energy dissipation through inter-particle friction. Such systems could provide high damping performance while remaining reusable and recyclable. Future research should focus on the experimental evaluation of these alternative materials, their interface behavior with timber substrates, and long-

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term performance under realistic service conditions. Advancing these sustainable solutions will be key to enabling the widespread adoption of timber floors in environmentally conscious, high-performance buildings.

Future work should also focus on long-term monitoring of similar floor systems under real occupancy to capture time-dependent effects such as creep, joint relaxation, and possible degradation of damping properties. Further experiments could also include rhythmic or resonant activities like jogging or group exercises, which impose different frequency content than standard walking. Additionally, the influence of floor finishes, insulation layers, and floating subfloors on vibration performance and occupant comfort remains an open area of investigation.

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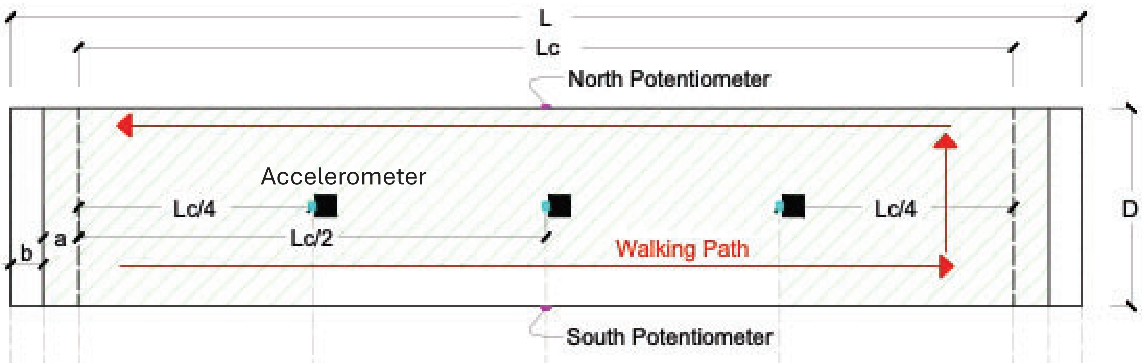

Figure 1. Images should be full width and print quality. Combine smaller images into a single item.

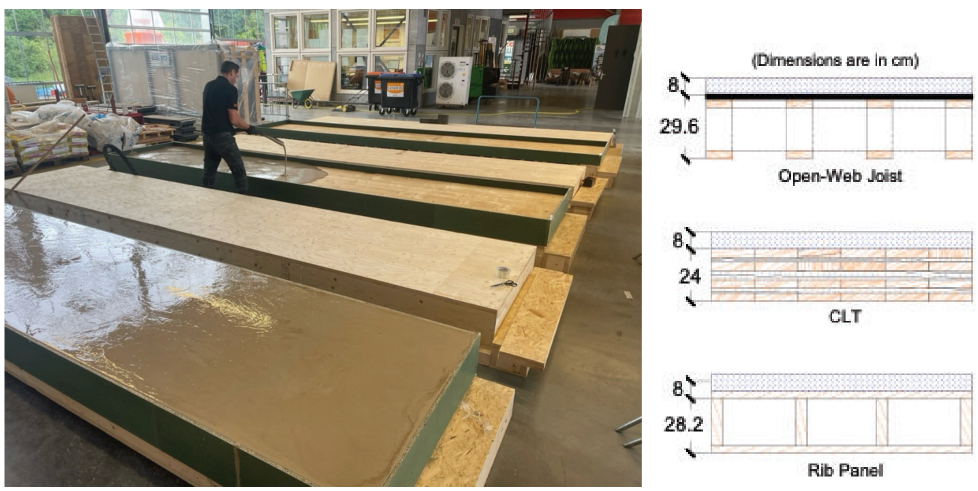

Figure 2. Timber floors during the pouring of the topping (left), and the cross-section of the tested 3 types of floors (right).

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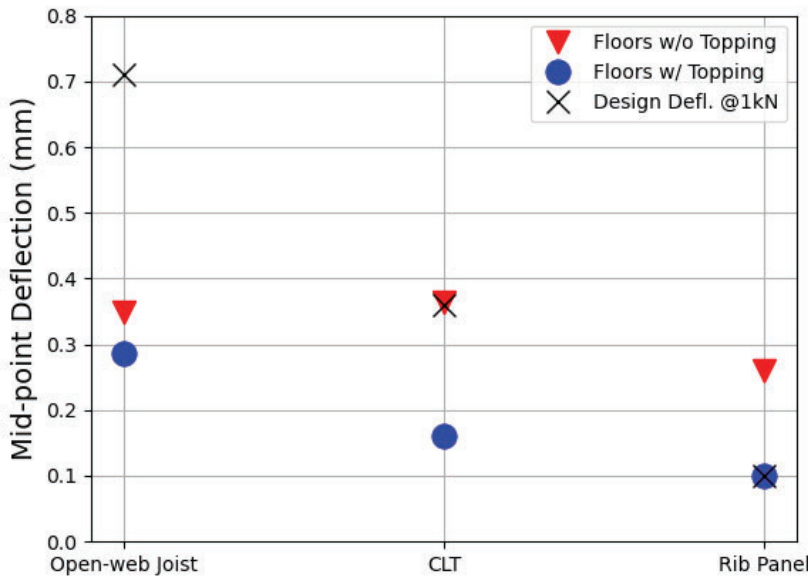

Figure 3. Measured mid-point deflections when the 1 kN point load is placed at L/2

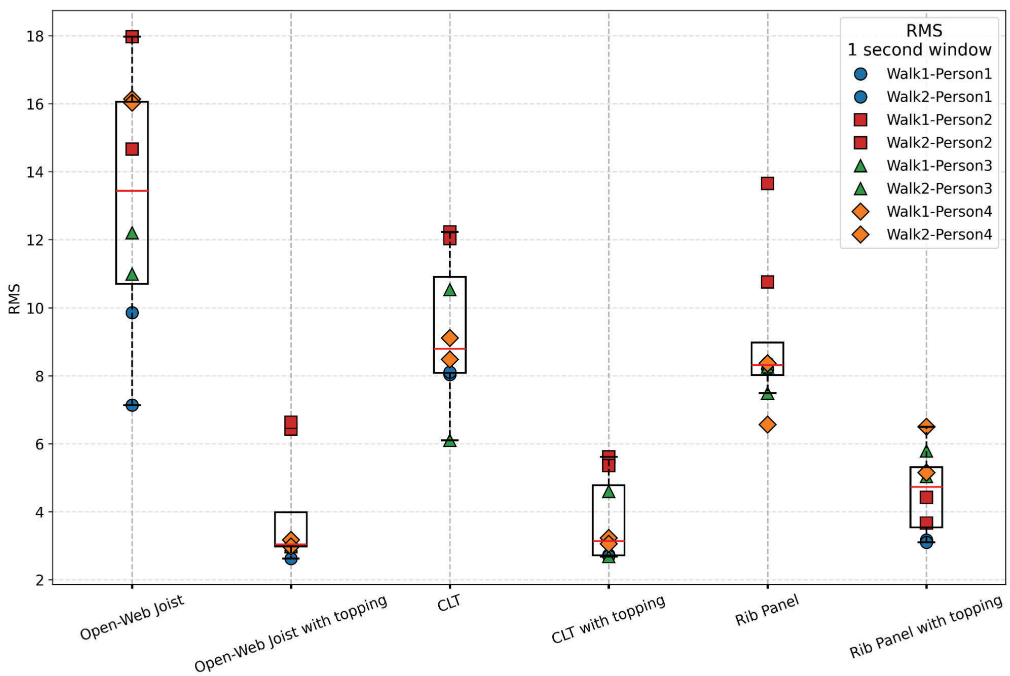

Figure 4. Measured RMS (mg) values with 1 second running window from walking tests.