

Article

Ride Vibration Exposure and Health Risk Assessment in Small Excavator-Based Timber Harvesting Operations in South Korea

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Abstract

Small harvesting compartments and steep terrain in South Korea favor harvesting systems in which a single machine performs multiple processes. Multifunctional systems based on small tracked excavators, equipped with a grapple saw for felling and a clambunk skidder for extraction, have therefore been increasingly adopted to address labor shortages and to improve operational safety. However, because these base machines lack a chassis suspension system and their operator seats provide limited vibration isolation, operators of small-excavator-based systems may be exposed to elevated levels of whole-body vibration (WBV) and shock vibration. This study quantified operator ride-vibration exposure and assessed the associated health risks during small-excavator-based timber harvesting in accordance with ISO 2631-1; the assessment was based on measured vibration exposure rather than on direct medical evaluation. Tri-axial accelerations were measured simultaneously at the operator seat and the cab floor of a 5-ton-class excavator over eight workdays, and one representative workday was analyzed at the work-element level. The harvesting process was divided into timber felling (machine travel, positioning, clearing, and cutting and bunching) and timber extraction (machine travel on forest roads, machine travel on skid trails, and loading and unloading). Exposure was evaluated using the frequency-weighted root-mean-square (RMS) acceleration, the crest factor (CF), and the total vibration dose value (TVDV). The CF exceeded 9 for all work elements, indicating shock-dominated vibration and justifying the TVDV as the primary evaluation metric. Timber extraction generated higher vibration exposure than timber felling, and the seat TVDV differed significantly among the work elements within each operation ($p < 0.001$). The highest seat TVDV occurred during loading and unloading ($123.05 \text{ m/s}^{1.75}$), exceeding the upper ISO 2631-1 Health Guidance Caution Zone limit for an 8-h exposure by more than eight times, and all major work elements exceeded the ISO 2631-1 health guidance limits. To our knowledge, this study provides the first work-element-level quantification of WBV exposure for small-excavator-based timber harvesting systems in South Korea. The findings underscore the need for improved seat suspension systems, vibration mitigation technologies, and vibration-aware work planning strategies.

Keywords: mechanized forest operations; ergonomics; ride vibration; shock vibration; operator exposure



Academic Editor: Kazuhiro Aruga

Received: 22 June 2026

Revised: 21 July 2026

Accepted: 25 July 2026

Published: 29 July 2026

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1. Introduction

Timber harvesting can pose significant safety risks to operators if proper safety guidelines and operational procedures are not followed, because operators are exposed to multiple occupational risk factors, including noise, whole-body vibration (WBV), repetitive movements, and challenging terrain conditions [1,2]. Excessive exposure to WBV has been associated with an increased risk of musculoskeletal disorders, reduced work performance, fatigue, and other adverse health effects [3–5]. Consequently, protecting operator health and safety has become a key priority in forest harvesting operations and in the efficient utilization of forest resources. To improve occupational safety in timber harvesting operations, numerous studies have quantified operator exposure to WBV and noise in mechanized harvesting systems and evaluated the associated health risks in accordance with international standards such as ISO 2631-1 [3–9].

Timber harvesting environments in Korea are typically characterized by small work compartments, short operation periods, a high proportion of steep terrain, and limited forest-road accessibility [10]. Under these conditions, work methods that allow a single machine to move quickly within the stand and to handle multiple processes are preferred, because they reduce equipment relocation and waiting time. Combination machines based on tracked excavators with bucket capacities of 0.3 m³ or less can perform felling, processing, and timber extraction with a single machine, and empirical studies have accordingly examined their productivity and economic efficiency at small-scale harvesting sites [11–13].

Although mechanization removes workers from many of the direct hazards of motor-manual felling, mechanized harvesting introduces machine-specific hazards of its own, including noise and, in grapple saw based systems, chain shot, in which a fragment of a broken saw chain is ejected at high velocity during cutting. Alongside these hazards, whole-body vibration remains a primary ergonomic risk factor for machine operators and is the focus of the present study. In addition, tracked excavators lack suspension systems in their base machines, and the suspension performance of operator seats is less effective than that of other specialized vehicles [14]. Because of these structural characteristics, small-excavator-based systems operated in Korean timber harvesting sites may expose operators to high levels of whole-body vibration and shock vibration [6,7,15]. Excessive exposure to whole-body vibration has been reported to increase the long-term incidence of musculoskeletal disorders, to deteriorate operator health, and to raise the risk of reduced work performance and occupational accidents [16,17]. In particular, vertical-axis vibrations in the frequency range of 0.5–16 Hz during excavator travel and operation include the human body resonance range. When combined with repeated shock vibrations caused by irregular ground conditions and the operation of work implements, lumbar compressive loads may increase, thereby elevating the risk of musculoskeletal disorders (MSDs) [18–20]. In addition, such vibration environments may degrade the visual performance of operators [21,22].

Regarding the ride vibration of forestry machines in Korea, previous studies have mainly examined vibration evaluation criteria for forestry vehicles and machinery [22], together with studies that analyzed forest-road surface characteristics generating vibration during the travel of vehicle-based forestry machines [23]. More recently, a work-operation-level WBV analysis of a tractor–timber trailer unit reported that vibration magnitudes differed significantly among individual forwarding operations, including between loaded and unloaded travel [24]. However, most previous studies have focused on vehicle ride comfort in relation to forest road surface conditions, rather than on operator exposure. As a result, no previous study has quantified work-element-specific WBV exposure and associated health risks in small-excavator-based timber harvesting systems operating in Korean forests. Moreover, systematic comparisons of vibration characteristics between

unit tasks and work elements based on ISO 2631-1 remain limited [25]. Although these previous studies identified the general risk potential of excavator-based operations, the exposure arising in each individual work element of felling and extraction, a prerequisite for element-targeted mitigation measures, has not yet been quantified.

Accordingly, this study aimed to quantify work-element-specific WBV exposure and assess associated health risks in small-excavator-based timber harvesting operations, using field measurements obtained under the steep-terrain, small-compartment conditions typical of Korean harvesting sites. The harvesting process was divided into timber felling and timber extraction operations, and tri-axial acceleration signals were measured simultaneously at the cab floor and operator seat. Vibration exposure was evaluated in accordance with ISO 2631-1 using weighted root mean square acceleration (WRMS), crest factor (CF; the ratio of the peak to the root-mean-square (RMS) acceleration), and total vibration dose value (TVDV). Furthermore, operator health risks and comfort levels were assessed using the Health Guidance Caution Zone (HGCZ) and comfort evaluation criteria defined in ISO 2631-1.

2. Materials and Methods

2.1. Study Area

The study was conducted in the experimental forest managed by the National Institute of Forest Science in Namyangju-si, Gyeonggi-do, Republic of Korea (Figure 1). The study site was a 0.56 ha clear-cut harvesting area located at 37°45'42" N, 127°10'43" E (WGS84), with an average slope of 39%. The stand was dominated by Japanese larch (47%) and mixed broadleaf species (40%). The average diameter at breast height (DBH) of the harvested trees was 22.1 cm, and the average stand density was 604 trees/ha. These stand and terrain characteristics reflect the operational conditions under which small excavator-based timber harvesting systems are frequently employed in Korean forests.

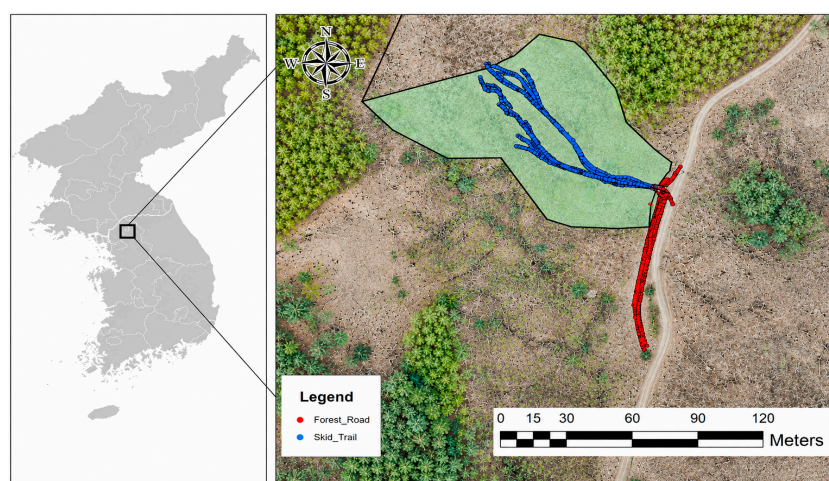


Figure 1. Experimental site.

2.2. Measurement Equipment and Methods

The timber harvesting system evaluated in this study was a small-excavator-based combi-machine used for both felling and extraction operations (Figure 2). The system is built on a 5-ton-class small excavator (EC60E, Volvo Construction Equipment, Gothenburg, Sweden) and equipped with a grapple saw for timber felling and a clambunk skidder for timber skidding. This configuration enabled multiple harvesting processes to be performed using a single machine; that is, both timber felling and timber extraction were carried out by the same base machine. Five-ton-class tracked excavators are among the most common

base machines for such combi-systems in Korea, because steep slopes, narrow forest roads, and small compartment areas limit the access and maneuverability of larger machines, and excavator-based systems of a comparable class (bucket capacity of 0.3 m³ or less) have been adopted in previous Korean harvesting studies [10–13]. According to national forestry statistics, excavators with a bucket capacity of 0.3 m³ or less (approximately 5-ton class) constitute the most widely held excavator class for forestry operations in Korea, accounting for 206 of 284 units (72.5%) in 2024 [26]. The EC60E was therefore selected as a configuration representative of small-excavator-based harvesting operations currently practiced in Korean forests. The operator performed all harvesting activities while seated on the original fabric-covered mechanical suspension seat installed in the Volvo EC60E [27]. The operator remained inside the enclosed cab during all grapple saw operations; the cab conformed to the roll-over and tip-over protective structure requirements (ROPS and TOPS), while dedicated chain-shot protective glazing was not specified for the machine.

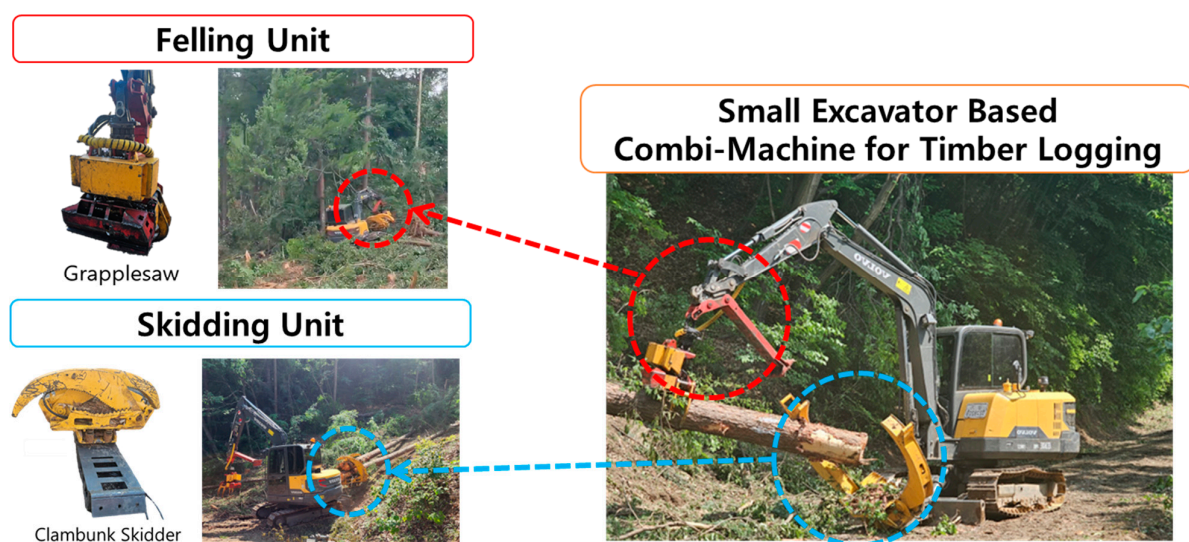


Figure 2. Small excavator-based combi-machine equipped with a felling and skidding unit for the timber harvesting system.

Ride vibration measurements were conducted for the excavator operator in accordance with ISO 2631-1. Tri-axial vibrations were measured simultaneously at the operator seat and cab floor using the measurement system shown in Figure 3. The vibration sensors were installed at the primary vibration transmission interfaces between the machine and the operator, namely the seat surface and cab floor. Seat vibration was measured using a tri-axial seat accelerometer (Type 4322, Brüel & Kjær, Nærum, Denmark) placed on the seat surface, and floor vibration was measured using a tri-axial accelerometer (Type 4321-V, Brüel & Kjær) mounted on the cab floor below the seat. Acceleration signals from all six channels were recorded simultaneously at a sampling frequency of 12.8 kHz using a PULSE LAN-XI multiple-module front-end (Brüel & Kjær), and the sensors were calibrated prior to the field measurements. The frequency weightings specified in ISO 2631-1 (W_d for the horizontal axes and W_k for the vertical axis, with the corresponding k multiplying factors) were applied during post-processing. To minimize variability associated with operator behavior, vibration exposure data were collected continuously from the same operator throughout the measurement period and acceleration data were recorded continuously over the entire work period, including rest and other non-productive periods. All work-element-level evaluations reported in this study, however, were computed only from the productive work-element intervals identified through video synchronization; unproductive periods were excluded from the work-element TVDV and eVDV evaluations and are

reported separately for reference. Measurements were conducted over eight workdays (total scheduled machine time of approximately 33.5 h), and the number of observation cycles obtained for each work element on the representative workday is reported with the results in Section 3.2. The measurements were obtained from a single operator, a single machine, and a single harvesting site; the scope of the study is therefore limited to the investigated system and operating environment.

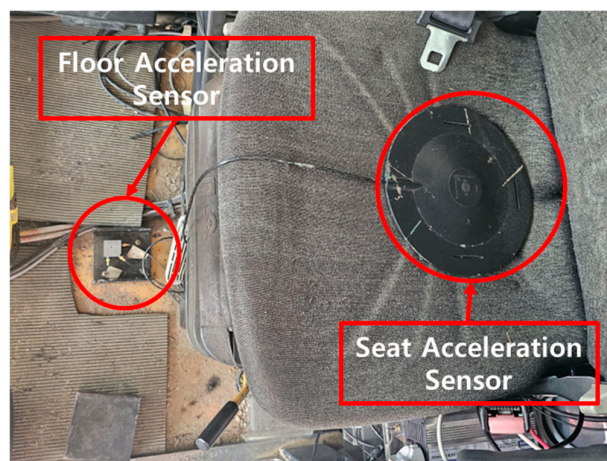


Figure 3. A vibration measurement system for monitoring operator exposure during timber harvesting operations using a small excavator.

2.3. Classification of Work Elements in Timber Felling and Timber Extraction Operations

For operators engaged in small-excavator-based timber felling and timber extraction operations, the recorded time–acceleration data contain vibration exposure associated with multiple work elements as well as non-productive activities, such as rest periods and routine machine inspection. Therefore, to quantify vibration exposure at the work element level, it was necessary to establish clear operational definitions, identify the start and end points of each work element, and classify the acceleration data according to the corresponding time intervals.

Based on previous studies [8,28,29], the work elements for timber felling and timber extraction operations were classified and defined as shown in Table 1. The classification framework was developed to maintain consistency with the representative work elements commonly used in mechanized timber harvesting studies. For timber extraction operations, machine travel was further divided into forest-road travel and in-stand travel because differences in terrain and travel-surface characteristics can substantially influence vibration exposure. Accordingly, these travel conditions were treated as separate work elements in the analysis. In the evaluated system, timber felling and timber extraction were performed as sequential operations: the machine first completed the felling operation in two to three passes, in which trees were felled with the grapple saw and bunched within the stand, and the bunched whole trees were subsequently extracted in a separate operation using the clambunk skidder along skid trails and forest roads to the landing. Both machine-travel elements of the timber extraction operation included loaded travel toward the landing and unloaded return travel, which were analyzed together without differentiation by load state.

To classify the measured time–acceleration data according to individual work elements, operational activities were continuously recorded using an ITB-8000QHD camera (ITRONICS Co., Ltd., Yongin-si, Republic of Korea) (2-megapixel, 30 fps) mounted inside the excavator cab. The camera was positioned to capture the operator’s field of view, enabling the start and end points of each work element to be identified and synchronized with the corresponding acceleration data during post-processing. To ensure consistent

segmentation between adjacent work elements, operationally defined transition criteria were applied. In particular, the boundary between the positioning and the cutting and bunching elements was defined by grapple-saw deployment: boom, arm, and cab-slewing movements performed before the saw was deployed were classified as positioning, whereas the interval from the onset of saw operation, including the concurrent bunching of felled trees with the grapple, was classified as cutting and bunching.

Table 1. Work elements in timber felling and timber extraction operations.

Work Phase	Work Elements	Definition
Timber Felling	Machine Travel	Relocation of an excavator between work locations through controlled driving operations.
	Positioning	Boom, arm, and cab movements performed to position the excavator for timber felling operations.
	Clearing	Removal of vines, logging residues, and other obstructions using the excavator attachment to secure and organize the work area.
	Cutting & Bunching	Cutting trees with the grapple saw and gathering felled whole trees into bunches for subsequent timber extraction operations.
	Unproductive Time	Periods during which the machine is idle or stopped for routine inspections, adjustments, or other non-productive activities.
Timber extraction	Machine Travel (Forest Road)	Travel of the excavator along forest roads while transporting timber with the clambunk skidder.
	Machine Travel (Skid Trail)	Off-road travel on skid trails within the stand while transporting timber with the clambunk skidder.
	Loading & Unloading	Loading or unloading timber at the landing using the excavator-mounted clambunk skidder while the machine remains stationary.
	Unproductive Time	Periods during which the machine is idle or stopped for equipment maintenance, adjustments, or operator rest.

2.4. Selection of a Representative Workday for Ride Vibration Evaluation

Across eight workdays during which the same equipment, operator, and work system were used, daily productivity of the timber felling and timber extraction processes was calculated, and a representative workday for ride vibration evaluation was selected. The tree identification numbers recorded in the daily work logs were matched with stem volume data in the tree inventory records to calculate the daily processed volume. This value was then divided by the machine operating time (scheduled machine hour, SMH), derived from a time study of the timber felling and timber extraction processes, to obtain process-specific productivity (m^3/SMH).

To quantitatively compare productivity variations among workdays, the mean and standard deviation of the daily productivity data were calculated, and the coefficient of variation (CV) was derived. The CV is an index used to compare relative dispersion among variables with different units and scales, and it has been widely applied in recent forest operations research to evaluate variability in productivity and harvester performance across workdays and work areas [30–33]. In addition, to determine the relative position of a specific workday's productivity within the overall distribution, a leave-one-out Z-score was employed, as expressed in Equation (1).

$$z_d = \frac{P_d - \bar{P}_d}{SD_d} \quad (1)$$

Here, P_d denotes the productivity of workday d , while $\bar{P}_d$ and SD_d represent the mean and standard deviation calculated from all other workdays excluding day d . A value of $|z_d| \leq 1$ indicates a workday that can represent the workdays as a whole, lying within ± 1 standard deviation of the mean. A value of $1 < |z_d| \leq 2$ indicates a workday with relatively higher or lower productivity, and a value of $|z_d| > 2$ indicates a statistically atypical workday [31,34].

As shown in Table 2, 21 May showed slightly higher productivity than the overall average in both the timber felling and timber extraction work phases, while its coefficients of variation were 20.9% and 41.6%, respectively, comparable to those of the other workdays. The absolute Z-scores for this date were 0.7 for timber felling and 0.8 for timber extraction, both less than 1. Unlike 8, 9, 22, and 23 May, which fell outside the mean ± 1 standard deviation range in at least one process, 21 May was evaluated as a typical workday representative of both processes. In addition, among the workdays that were representative in both processes, 21 May had the longest working time (7.11 h), ensuring a sufficient number of observation cycles and an adequate processed volume. Therefore, 21 May was selected as the representative workday reflecting the productivity and ride vibration characteristics of the excavator-based timber felling and timber extraction system. In line with previous studies in which productivity statistics were used to identify representative working conditions for forest machine operations [33], the representative workday was selected solely from the productivity data, independently of the vibration measurements. Because the subsequent analyses focus on this single representative workday, day-to-day variability in vibration exposure was not quantified in this study.

Table 2. Daily productivity of timber felling and timber extraction work phases and their assessment of typicality.

Work Day (Hour)	Timber Felling Productivity (m ³ /SMH)	Timber Felling CV (%)	Timber Felling $ z_d $	Typicality	Timber Extraction Productivity (m ³ /SMH)	Timber Extraction CV (%)	Timber Extraction $ z_d $	Typicality
8 May (4.03)	8.7	19.7	1.3	Slightly high	3.1	42.1	0.4	Representative
9 May (7.11)	5.4	17.7	1.5	Slightly low	2.3	40.6	0.3	Representative
20 May (2.67)	8.0	21.0	0.7	Representative	2.9	42.1	0.3	Representative
21 May (7.11)	8.1	20.9	0.7	Representative	3.4	41.6	0.8	Representative
22 May (2.16)	7.8	21.1	0.5	Representative	4.0	33.3	2.5	Non-typical
23 May (3.35)	5.1	16.4	2.0	Slightly low	1.1	30.0	2.1	Non-typical
24 May (4.54)	6.1	19.8	0.8	Representative	2.1	39.5	0.6	Representative
31 May (2.54)	8.0	20.9	0.7	Representative	2.0	38.9	0.7	Representative

In Table 2, typicality was classified from the leave-one-out Z-score as representative ($|z| \leq 1$), slightly high or low ($1 < |z| \leq 2$), or nontypical ($|z| > 2$); the working time of each workday is given in the first column. Because the operator, machine, and work system were identical across all workdays, the day-to-day differences in productivity are attributable mainly to spatial variation within the harvesting site—such as local slope, residual-stand conditions, tree size, and extraction distance of the trees processed on each day—which were not recorded as day-level covariates in this study.

2.5. Data Acquisition and Analysis Methods

The evaluation values for each work element were compared statistically. One-way ANOVA was applied to the seat TVDV values of individual work cycles, with each work cycle treated as the observational unit. Because all cycles were performed by a single operator on a single machine, ANOVA was used to test differences among the work elements within the investigated system, and the results are not intended as population-level inferences. Normality and homogeneity of variances were assessed for each work element using the Shapiro–Wilk test [35] and Levene’s test [36], respectively. Post hoc comparisons were conducted using Tukey’s HSD test [37] when variances were homogeneous and the Games–Howell test [38] otherwise. Comparisons were performed using the seat measurements, excluding unproductive periods. Operation-level exposure, for which sufficient independent work cycles were not available, is reported descriptively. All statistical analyses were performed in R (version 2025.05.1+513; R Foundation for Statistical Computing, Vienna, Austria), with statistical significance set at $\alpha = 0.05$; exact p -values are reported, and values below 0.001 are denoted as $p < 0.001$.

Figure 4 presents a schematic overview of the quantitative evaluation procedure for operator ride vibration from the perspectives of health risk and comfort in accordance with ISO 2631-1. First, signals along the x , y , and z axes were measured at the operator seat and the cab floor. Frequency weighting functions and correction factors specified in ISO 2631-1 were then applied to obtain the axis-specific weighted accelerations, which were subsequently combined vectorially into an equivalent frequency-weighted acceleration. The CF was used to determine whether the basic RMS method was appropriate. When the CF was less than 9, the total weighted RMS acceleration (TWRMS)—the vector sum of the axis-specific frequency-weighted RMS accelerations—was used for evaluation. In vibration environments characterized by shocks or transient events ($CF \geq 9$), the TVDV was applied, and comparative evaluations were performed using time-normalized values according to exposure duration. Finally, the resulting evaluation values were compared with the health guidance zones and comfort response criteria specified in ISO 2631-1 to determine the health risk level and comfort classification for each work element. Although ISO 2631-5 [19] provides a complementary method for evaluating vibration containing multiple shocks on the basis of predicted spinal response, the ISO 2631-1 framework was adopted in this study because its VDV-based procedure is explicitly recommended for vibration environments with crest factors of 9 or higher, and because the objective of this study was to assess work-element exposure against the health guidance and comfort criteria defined within ISO 2631-1. A complementary evaluation based on the ISO 2631-5 spinal response model is identified as a subject for future research.

The health guidance zones based on the equivalent frequency-weighted acceleration specified in ISO 2631-1 are presented in Table 3, while the corresponding comfort response classifications defined by the same standard are shown in Table 4. When the evaluation was conducted using the TVDV, the measured vibration exposure was converted into an estimated vibration dose value (eVDV) in accordance with the ISO 2631-1 evaluation method using Equation (2). The resulting eVDV was then compared with the health guidance zones and comfort response criteria.

$$eVDV = 1.4a_w(T)^{\frac{1}{4}} \quad (2)$$

where $eVDV$ = Estimated vibration dose value ($\text{m/s}^{1.75}$).

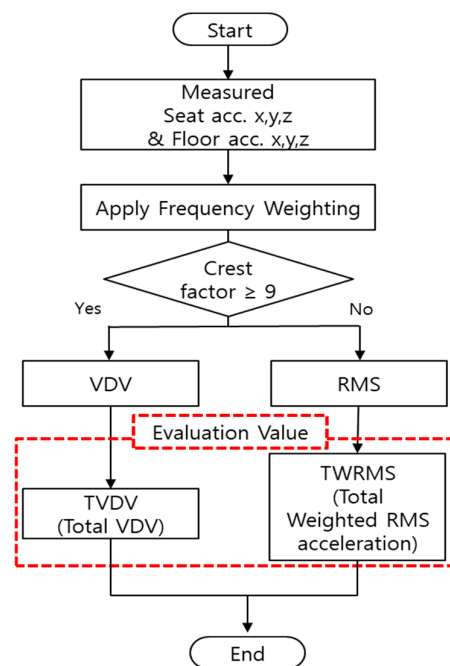


Figure 4. Overview diagram of ISO 2631-1 for health and comfort evaluation.

Table 3. Whole-body vibration exposure limits and potential health guidance of ISO 2631-1.

Health Guidance	TWRMS (m/s^2)	TVDV ($\text{m/s}^{1.75}$)
Exposure limit for four hours	1.143	17.529
Exposure limit for eight hours	0.808	14.736
Potential health risk limit for four hours	0.572	8.772
Potential health risk limit for eight hours	0.404	7.368

Table 4. Comfort reaction for total weighted RMS (TWRMS) and total vibration dose value (TVDV) levels of ISO 2631-1.

Comfort Reaction	TWRMS (m/s^2)	TVDV ($\text{m/s}^{1.75}$)
Extremely uncomfortable	Greater than 2	Greater than 36.48
Very uncomfortable	1.25~2.5	22.8~45.6
Uncomfortable	0.8~1.6	14.6~29.2
Fairly uncomfortable	0.5~1	9.1~18.2
A little uncomfortable	0.63~0.315	5.7~11.5
Not uncomfortable	Less than 0.315	Less than 5.7

In Equation (2), a_w denotes the frequency-weighted RMS acceleration (m/s^2) and T denotes the exposure duration (s); TVDV and eVDV values are expressed in $\text{m/s}^{1.75}$, the unit of the vibration dose value. The health and comfort assessments in this study were conducted with reference to the ISO 2631-1 guidance for 8-h (and, where indicated, 4-h) reference exposure periods (Table 3); they are based on measured vibration exposure and do not involve direct medical evaluation of the operators.

3. Results and Discussion

3.1. Characteristics of Exposed Ride Vibration in Excavator-Based Timber Felling and Timber Extraction Operations

As shown in Figure 5, throughout the excavator-based timber felling and timber extraction operations, both floor and seat vibrations exhibited a CF ≥ 9 in at least one axis. In the timber felling operation, the machine travel work element showed CF values exceeding 9 on most axes; the floor vibration was particularly high on the Z-axis, whereas the seat vibration exceeded 9 on the X-axis during the positioning and clearing work elements. In the timber extraction operation, every work element—machine travel (forest road), machine travel (skid trail), and loading and unloading—exhibited CF values above 9 for both floor and seat vibrations, indicating a work environment in which shock or transient vibrations occurred frequently.

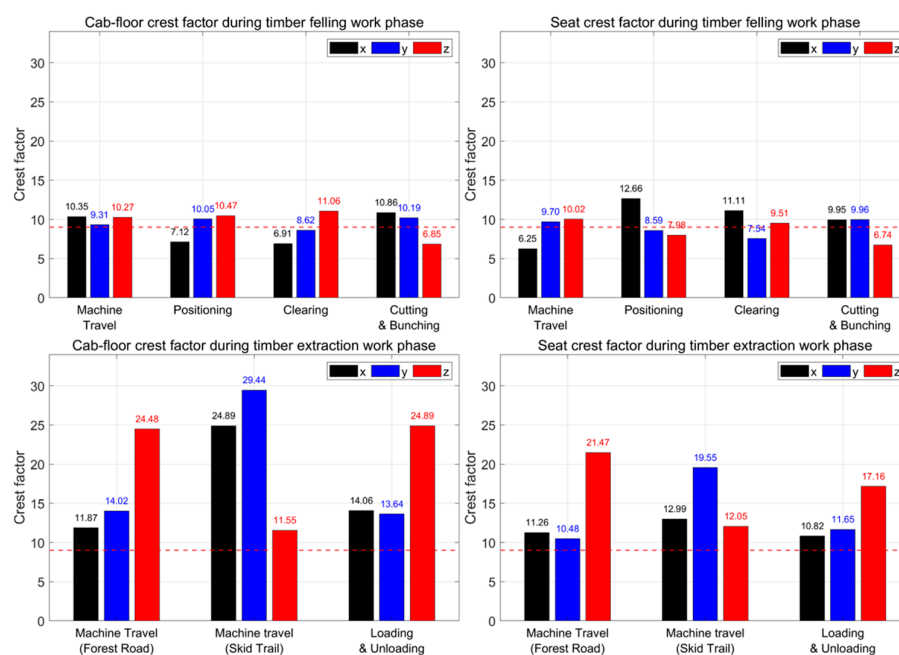


Figure 5. Crest factor measured at the cab floor and operator seat for each work element. (The red dashed line indicates a crest factor of 9).

In light of previous ride vibration assessments and the ISO 2631-1 criteria, vibration exposure in such multiple-shock environments is difficult to evaluate adequately using the equivalent frequency-weighted acceleration (total weighted RMS, TWRMS) alone [39,40]. When the CF exceeds 9, a small number of large peak components are present in the vibration signal and tend to dominate the overall exposure; in such cases, the use of the TVDV, which reflects these peaks through fourth-power accumulation, is recommended. Accordingly, the TVDV rather than the TWRMS was adopted in this study as the primary evaluation parameter for analyzing the ride vibration characteristics and for assessing health and comfort at the work-element level.

3.2. Work-Element-Level TVDV and Statistical Comparison

The TVDV values for operators engaged in the small-excavator-based timber felling and timber extraction operations are summarized in Table 5 and Figure 6. In the distribution of TVDV at the unit-operation level, both the floor and seat TVDV values for the timber extraction operation showed an overall upward shift and greater dispersion than those for the timber felling operation. This trend is attributed to the cumulative effects of repeated skidding, loading and unloading, and travel over uneven surfaces during timber

extraction, which substantially increased vibration exposure over extended periods. A similar tendency has been reported in previous studies of the ride vibration exposure of skidder operators [41].

In the timber felling operation, the machine travel work element exhibited mean TVDV values of $29.74 \text{ m/s}^{1.75}$ at the floor and $17.55 \text{ m/s}^{1.75}$ at the seat. This is presumed to reflect the combined effects of the low-frequency continuous vibration during travel over irregular mountainous terrain and the shock vibration generated when obstacles were traversed. In the clearing and the cutting and bunching work elements, relatively high TVDV values were observed at both the floor and the seat, mainly owing to the operation of the work implement and collisions between logs and residual materials. In contrast, during the positioning work element, the seat TVDV ($44.50 \text{ m/s}^{1.75}$) exceeded the floor TVDV ($21.77 \text{ m/s}^{1.75}$), corresponding to a seat-to-floor transmissibility above 100%. This is presumed to result from momentary operator–seat separation and re-contact caused by the abrupt boom, arm, and cab-slewing movements of the positioning element [42].

To further quantify the vibration isolation performance of the operator seat, the seat effective amplitude transmissibility (SEAT) was calculated for each work element as the ratio of the seat TVDV to the floor TVDV, expressed as a percentage; SEAT values below 100% indicate attenuation by the seat, whereas values above 100% indicate that the vibration at the seat exceeded that at the floor. In the timber felling operation, the SEAT values were 59.0% for machine travel, 204.4% for positioning, 56.8% for clearing, and 71.3% for cutting and bunching. In the timber extraction operation, the SEAT values were 74.9% for machine travel on forest roads, 38.3% for machine travel on skid trails, and 46.4% for loading and unloading. Accordingly, the mechanical suspension seat attenuated the severe shock-dominated inputs of the extraction elements, whereas during the positioning element the vibration recorded at the seat was approximately twice that at the floor, presumably owing to the momentary operator–seat separation described above.

In the timber extraction operation, marked differences among work elements were observed depending on the travel path and the role of the work implement. The mean TVDV for machine travel on forest roads was $34.21 \text{ m/s}^{1.75}$ at the floor and $25.63 \text{ m/s}^{1.75}$ at the seat, whereas for machine travel on skid trails the corresponding values increased substantially to $99.04 \text{ m/s}^{1.75}$ and $37.95 \text{ m/s}^{1.75}$. This increase is attributed to the frequent impact forces caused by irregular obstacles such as rocks, roots, and slopes on skid trails, which induced stronger vibrations than those encountered on forest roads. Consistent with this interpretation, a post-hoc analysis of terrain roughness along the routes travelled on the representative workday, derived from a fine-scale DEM using zonal statistics in QGIS (version 4.0; QGIS Development Team, Open Source Geospatial Foundation, Beaverton, OR, USA), indicated a mean roughness index of approximately $1.08 (\pm 0.32)$ for the skid-trail segments and $0.25 (\pm 0.24)$ for the forest-road segments—a roughly four-fold difference that provides an objective correlate for the elevated vibration observed on skid trails, consistent with the established dependence of ride vibration and comfort on surface roughness [23]. In addition, obstacle- and slope-constrained travel on skid trails prolongs the traverse time while producing high-amplitude shocks, and the fourth-power weighting of the TVDV makes the metric particularly sensitive to such shock components; a comparable terrain dependence of WBV has been reported for forwarding operations on rough ground [24].

Table 5. Results of statistical analysis of ride vibration by work elements and measured positions.

Work Operations		Timber Felling										Timber Extraction							
No. of Cycles		7										13							
Time (min)		129.65										172.83							
Measured Position		Floor				Seat						Floor				Seat			
Peak (m/s ^{1.75})		51.81				57.67						308.53				142.32			
Mean (m/s ^{1.75})		23.79				21.29						100.99				47.50			
Work Elements		Machine travel		Positioning		Clearing		Cutting &Bunching		Unproductive time		Machine travel (Forest Road)		Machine travel (Skid Trail)		Loading &Unloading		Unproductive time	
No. of Cycles		30		60		23		76		58		26		24		52		28	
Time (min)		9.13		13.12		15.22		25.60		66.58		54.47		33.77		61.07		23.53	
Measured Position		Floor	Seat	Floor	Seat	Floor	Seat	Floor	Seat	Floor	Seat	Floor	Seat	Floor	Seat	Floor	Seat	Floor	Seat
Peak (m/s ^{1.75})		50.67	28.94	35.68	57.67	38.84	24.28	51.81	48.52	19.78	15.80	47.94	34.61	111.58	54.75	308.53	142.32	17.26	23.09
Mean (m/s ^{1.75})		29.74	17.55	21.77	44.50	28.71	16.30	33.05	23.57	5.65	4.54	34.21	25.63	99.04	37.95	265.10	123.05	5.63	3.38

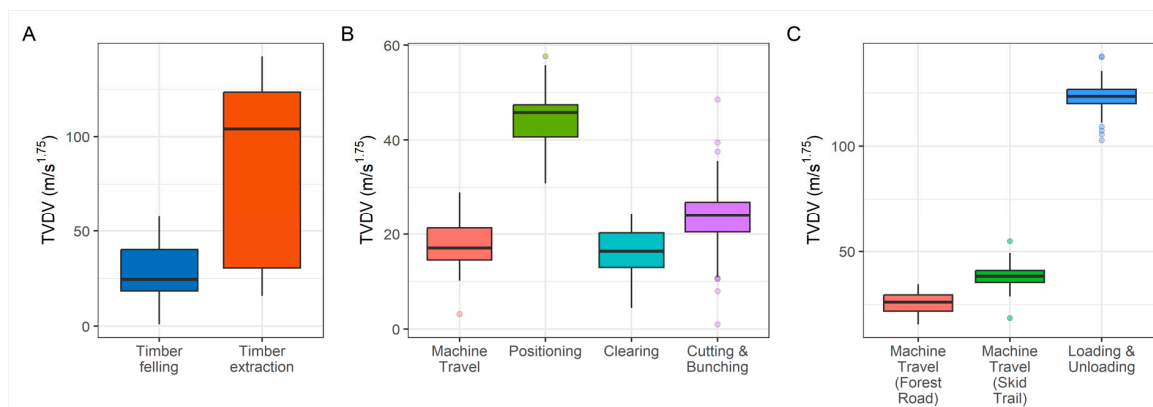


Figure 6. Box plots of the seat TVDV (unproductive periods excluded) during excavator-based timber felling and timber extraction: (A) comparison between the timber felling and timber extraction operations; (B) work elements of the timber felling operation; (C) work elements of the timber extraction operation.

As shown in Figure 6, the seat TVDV differed clearly among work elements. At the work-phase level, timber extraction showed a higher and more dispersed seat TVDV than timber felling (Figure 6A). Among the timber felling work elements (Figure 6B), the seat TVDV differed significantly ($F(3,185) = 207.9$, $p < 0.001$): the positioning element showed the highest seat TVDV ($44.50 \text{ m/s}^{1.75}$), significantly exceeding all other felling elements ($p < 0.001$), and the cutting and bunching element ($23.57 \text{ m/s}^{1.75}$) was significantly higher than machine travel ($17.55 \text{ m/s}^{1.75}$) and clearing ($16.30 \text{ m/s}^{1.75}$) (both $p < 0.001$), whereas machine travel and clearing did not differ significantly ($p = 0.89$). Among the timber extraction work elements (Figure 6C), the seat TVDV also differed significantly ($F(2,99) = 2092.3$, $p < 0.001$): loading and unloading recorded a markedly higher seat TVDV ($123.05 \text{ m/s}^{1.75}$) than machine travel on skid trails ($37.95 \text{ m/s}^{1.75}$) and on forest roads ($25.63 \text{ m/s}^{1.75}$), and skid-trail travel was in turn significantly higher than forest-road travel ($p < 0.001$ for all pairwise comparisons). These comparisons confirm that operator seat vibration was concentrated in specific work elements—positioning within timber felling and, most prominently, loading and unloading within timber extraction.

3.3. Health Risk Assessment Using TVDV

The results of the ride vibration exposure assessment are shown in Figure 7. In both the timber felling and timber extraction operations, the vibration levels measured at both the cab floor and the seat exceeded the thresholds regarded as significant for operator health. In particular, numerous cases exceeded the health guidance eVDV reference value of $14.74 \text{ m/s}^{1.75}$, indicating that the operators were exposed to health risks—such as musculoskeletal disorders and other potential adverse effects—arising from vibration exposure at these levels sustained over an 8-h working day.

In the timber felling operation, the floor TVDV values were higher than the seat TVDV values in the machine travel, clearing, and cutting and bunching work elements, with the highest floor TVDV observed in the cutting and bunching element. In contrast, during the positioning element, the seat TVDV was substantially higher than the floor TVDV, corresponding to a SEAT value of 204.4%; as described in Section 3.2, this is presumed to reflect momentary operator–seat separation and re-contact.

In the timber extraction operation, overall health risk levels were higher than those observed in the timber felling operation. In particular, the loading and unloading element recorded the highest values among all work elements, with floor and seat TVDV reaching approximately $250 \text{ m/s}^{1.75}$ and $120 \text{ m/s}^{1.75}$, respectively. Machine travel on skid trails also showed markedly high values, with floor TVDV of approximately $94 \text{ m/s}^{1.75}$ and

seat TVDV of approximately $37 \text{ m/s}^{1.75}$, far exceeding the health guidance limits. These results indicate that repeated shock vibrations generated during work implement operation and heavy load handling impose a greater burden on operator health than simple travel-related vibrations.

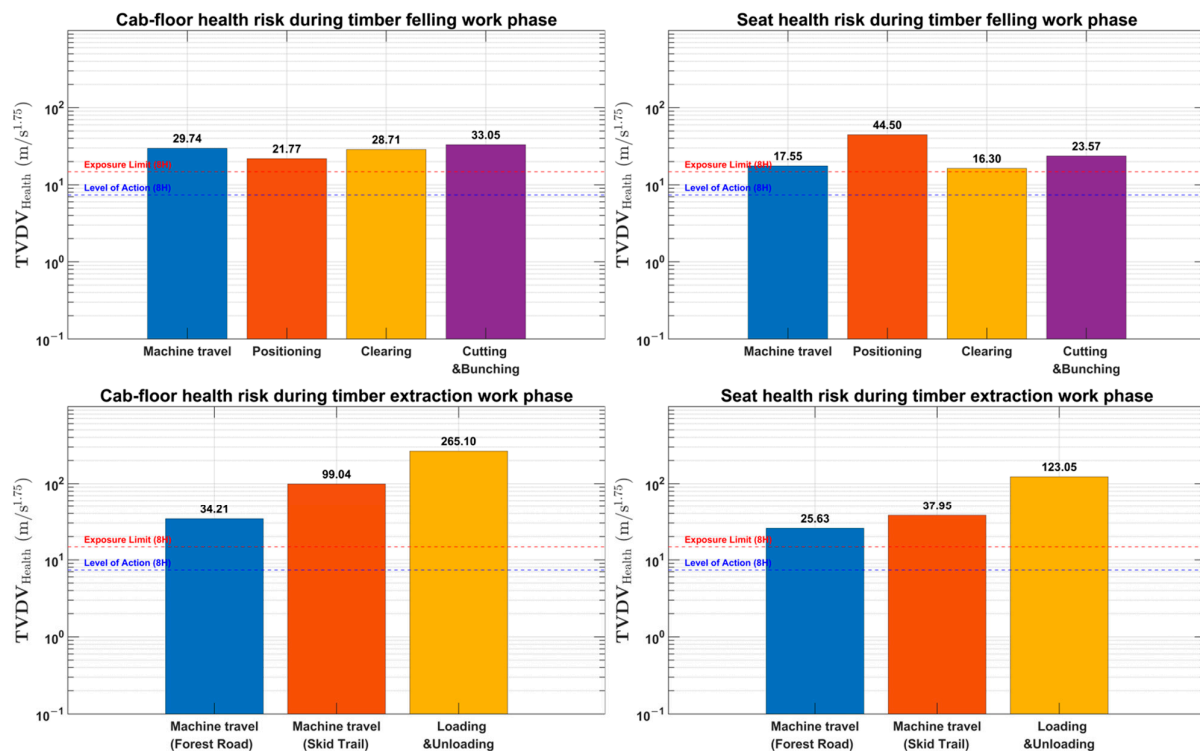


Figure 7. Health risk assessment by work element for excavator-based timber felling and timber extraction based on TVDV (The red dashed line denotes the exposure limit for eight hours and the blue dashed line the potential health risk limit for eight hours, as defined in ISO 2631-1).

These trends are consistent with findings from previous studies of forestry machine operators [6,16]. Research on forwarder operators has reported that ride vibration exposure varies significantly among work elements and increases substantially during implement operation phases, such as loading and unloading, compared with simple travel segments [16]. Experimental studies have likewise shown that the highest vibration exposure occurs in segments where work implement operation is combined with travel over irregular terrain during forwarder operations [8,28]. Studies of fully mechanized cut-to-length (CTL) systems have also reported, on the basis of VDV-based evaluations, numerous cases in which vibration exposure exceeded the ISO 2631-1 health guidance zones under various working conditions [6,7]. In these studies, cumulative exposure increased markedly during the loading, unloading, and machine-travel stages. These findings are consistent with the present results, in which the highest TVDV values were observed in the machine travel (skid trail) and loading and unloading work elements of the timber extraction operation [25].

The TVDV levels observed in this study were nevertheless generally higher than those reported in the existing literature for forwarders and harvesters operating in European regions [17]. In the small-excavator-based systems investigated here, this difference is attributed to the absence of a chassis suspension system in the base machine, unlike purpose-built forestry machines, and to the direct transmission of multi-axial shock vibration to the operator's seat during in-stand travel and work implement operation. The risk of ride vibration exposure in excavator-based combined work systems may therefore be comparable to, and under certain operating conditions even exceed, that of conventional purpose-built forestry machines.

3.4. Comfort Assessment Using TVDV

The assessment of operator comfort with respect to ride vibration is presented in Figure 8. Overall, the timber extraction operation exhibited poorer comfort conditions than the timber felling operation. Among the timber extraction work elements, the highest vibration load occurred during loading and unloading, with TVDV values of $252.47 \text{ m/s}^{1.75}$ at the floor and $117.67 \text{ m/s}^{1.75}$ at the seat. Under the comfort criteria of ISO 2631-1, these levels correspond to “extremely uncomfortable,” indicating that the repeated impacts and load variation during loading and unloading substantially increased the perceived discomfort for operators. The relative contribution of implement-side shocks during loading and unloading could not be characterized directly in this study because boom-tip accelerations were not measured; capturing these signals is identified below as a subject for future research.

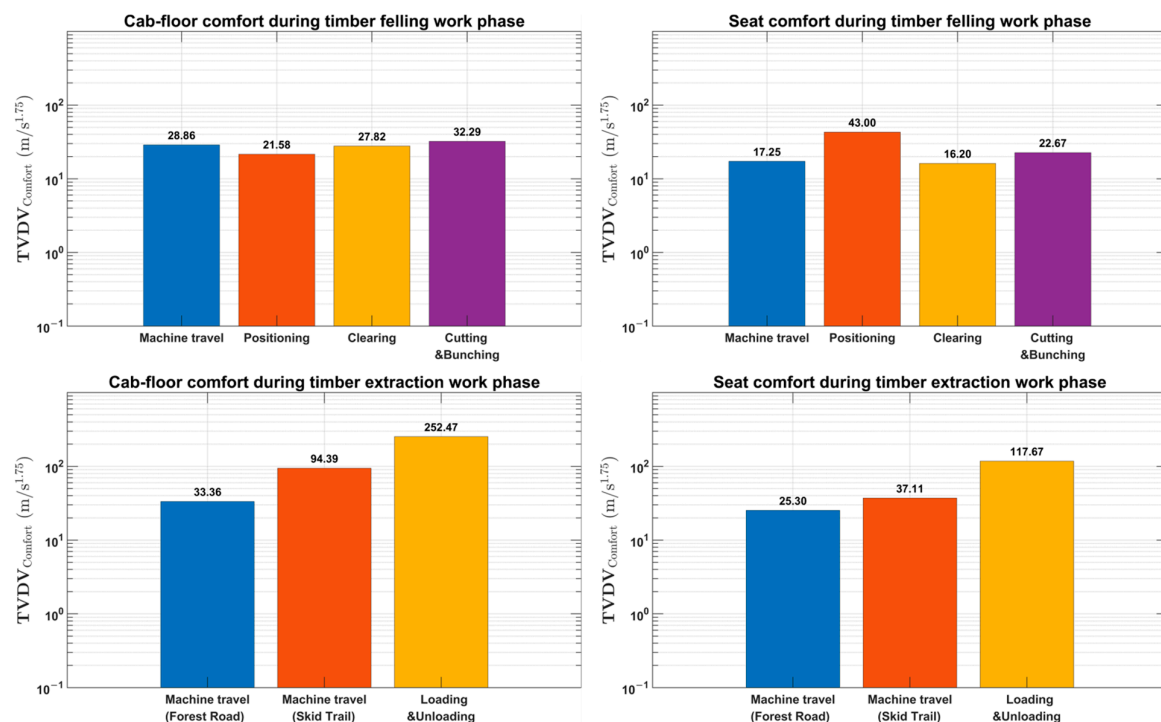


Figure 8. Comfort assessment by work element for excavator-based timber felling and timber extraction based on TVDV.

The next highest vibration load occurred during machine travel on skid trails, where the floor and seat TVDV values were $94.39 \text{ m/s}^{1.75}$ and $37.11 \text{ m/s}^{1.75}$, respectively, falling mostly within the “very uncomfortable” or “extremely uncomfortable” categories. This is presumed to result from the repeated impacts generated by uneven surfaces, bends, and slopes within the forest stand, which were transmitted to the operator’s seat with little attenuation. Machine travel on forest roads also reached “very uncomfortable” levels at both the floor and the seat, indicating that a substantial vibration burden existed even during forest road travel alone.

The work elements of the timber felling operation were generally rated between “uncomfortable” and “very uncomfortable.” In particular, the cutting and bunching and the clearing elements tended toward degraded comfort ratings, owing to the repeated impacts associated with boom movement and work implement operation. The machine travel element likewise fell within the “uncomfortable” to “very uncomfortable” range at both measurement positions. In contrast, during the positioning element, although the machine remained stationary, the seat TVDV exceeded the floor TVDV (SEAT = 204.4%),

presumably owing to the momentary operator–seat separation described in Section 3.2, resulting in relatively high perceived discomfort associated with seat vibration.

Previous studies of ride vibration comfort among forestry machine operators have consistently reported that perceived discomfort varies significantly among work elements [16,28]. Ride vibration exposure and perceived discomfort increase markedly during processes involving work implement operation and load variation, such as loading and unloading, compared with simple travel segments. Segments combining irregular-terrain travel with work implement operation have been shown to frequently elicit responses of “very uncomfortable” or higher under the ISO 2631-1 comfort criteria. These trends are consistent with the present findings, in which the highest TVDV values and the most severe deterioration in comfort ratings were observed in the loading and unloading and machine travel (skid trail) elements.

The comfort-related TVDV levels observed in this study were likewise higher than those reported for purpose-built forestry machines [16,27,28], reflecting the same structural limitation noted above. As a result, the comfort degradation reported in previous studies was more pronounced, concentrated in specific work elements—particularly machine travel on skid trails and loading and unloading. Building on these findings, several directions for future research emerge. First, as vibration environments in this study were characterized by crest factors of 9 or higher, a complementary evaluation based on the ISO 2631-5 spinal-response model would provide additional insight into the multi-shock component of exposure. Second, future seat design and evaluation protocols should move beyond the current ISO 7096 framework, which focuses on vertical (z-axis) responses, to incorporate field-measured multi-axis and shock vibration characteristics; overseas case studies have reported reductions in ride-vibration exposure of more than 30% when combined shock-mitigation devices and work-environment improvements were adopted [43,44]. Third, the phased introduction of remote-control and autonomous operation technologies for timber harvesting machinery deserves further evaluation as a means of reducing operator exposure [24,45]. Finally, follow-up studies should broaden the measurement design to include a wider range of operators, machine configurations, harvesting systems, and site conditions, together with load-state classification of travel elements and instrumented measurements of boom-tip accelerations during loading and unloading, so that the causal drivers of exposure can be resolved more directly.

4. Conclusions

This study measured and analyzed the ride vibration generated during small-excavator-based timber felling and timber extraction operations in Korean forests in accordance with ISO 2631-1. By subdividing the entire process into individual work elements for a single machine and operator and quantifying the vibration transmitted to the cab floor and seat by means of the TVDV, the ride vibration exposure characteristics of a small-excavator-based timber harvesting system were comprehensively identified. In all work elements, the crest factor exceeded 9, indicating an exposure environment dominated by repeated shock or transient vibration. This demonstrates that evaluation based solely on the conventional TWRMS is insufficient, and supports the use of a TVDV-based assessment that accounts for peak vibration components, consistent with reports of CF values exceeding 9 in the construction and defense machinery sectors and with the ISO 2631-1 recommendation to apply TVDV-based procedures under such conditions [46–48].

Work-element-level analysis revealed that segments involving work-implement operation consistently generated higher vibration loads than simple travel segments. In the timber felling operation, the machine travel segments combined low-frequency continuous vibration over irregular terrain with instantaneous shocks when passing obstacles such as

rocks and roots. The positioning segment showed elevated seat-level exposure, presumably owing to the momentary operator–seat separation described in Section 3.2, and the clearing and the cutting and bunching segments generated shock vibration from collisions between the work implement and the ground, residual materials, or logs. In the timber extraction operation, the machine travel (forest road) segment showed relatively lower levels with short-duration shocks at uneven surfaces and bends, whereas the machine travel (skid trail) segment exhibited substantially higher TVDV values owing to frequent irregular obstacles. In the loading and unloading segment, although travel-related vibration was minimal, impacts applied to the boom and attachments during timber handling were transmitted to the cab, producing the highest TVDV values among all work elements, consistent with previous findings that shock-type vibration dominates during loading and unloading [49].

Health risk assessment showed that all work elements exceeded the 8-h exposure limits specified in ISO 2631-1. In particular, the loading and unloading and machine travel (skid trail) segments greatly exceeded the upper health guidance limits, suggesting a high likelihood of adverse effects such as musculoskeletal disorders and lumbar compression under long-term exposure. Comfort evaluation further indicated that many segments corresponded to “very uncomfortable” or “extremely uncomfortable” levels, closely associated with the high TVDV values in repeated-shock segments. When the TVDV levels derived in this study are applied to the ISO 2631-1 health guidance zones, the safe and sustainable exposure duration falls well below the 8-h reference period, with some work elements indicating permissible exposure times of less than 10 min.

These findings indicate that reducing ride vibration in small-excavator-based timber harvesting operations will require, as a priority, the development and application of seat suspension systems with multi-axis damping, together with shock-absorbing devices installed along the transmission path from the work implement to the upper structure and seat. The current ISO 7096 [49] seat performance test focuses primarily on vertical (z-axis) responses and therefore has limitations in reflecting the multi-axis, shock-dominated environments observed in the field [50]. This study was conducted using a single operator and a single excavator-based timber harvesting system under specific operational conditions. Therefore, the results should be interpreted as representative of the investigated work environment rather than as being directly generalizable to all excavator-based timber harvesting operations. In addition, because the ride vibration analysis was based on a single representative workday selected using productivity statistics, day-to-day variability in vibration exposure across the full measurement period was not quantified. Directions for future research addressing these limitations, including complementary ISO 2631-5-based shock evaluations, load-state classification of travel elements, boom-tip acceleration measurements, and improved seat evaluation protocols, are discussed in Section 3.4.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/f17080887/s1>, Data S1: Vibration_Raw_Data.xlsx, containing the work-time and work-element records, the processed acceleration data compiled for each work element for the cab floor and the operator seat, and the crest factor, health risk, and comfort evaluation results for the representative workday.

Author Contributions: Conceptualization, H.-S.J., J.-H.O. and S.-K.H.; methodology, H.-S.J., H.-S.M. and J.-H.O.; formal analysis, H.-S.J.; investigation, H.-S.J. and J.-H.O.; writing—original draft preparation, H.-S.J.; writing—review and editing, J.-H.O. and S.-K.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Korea Forest Service (Korea Forestry Promotion Institute), grant numbers 2023491A00-2325-AA02 and FO0200-2025-01-2025.

Data Availability Statement: The original data presented in the study are included in the article and Supplementary Materials; further inquiries can be directed to the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HGCZ	Health Guidance Caution Zone
ISO	International Organization for Standardization
MSDs	Musculoskeletal Disorders
TVDV	Total Vibration Dose Value
TWRMS	Total Weighted Root Mean Square (acceleration)
VDV	Vibration Dose Value
WRMS	Weighted Root Mean Square

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