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Measuring Physiological Workload and Vehicle Movement While Driving Timber Forwarders in Both Forward and Reverse Travel

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Abstract

Physiological workload during timber forwarder operations presents a heavy burden due to the unpaved forestry occupational roads, and steep terrain in Japan; however, the relationship between physiological workload and vehicle movement is not clear. To assess the workload of operating forwarders, changes in heart rate and vehicle movements were measured. Five male subjects aged 35 to 53 years were assessed. The subjects were tested twice while operating a forwarder with an empty load: first driving forwards, then driving in reverse. Three inertial measurement units were used to calculate travel speed, tilt angle, and turning speed, and heart rate was assessed using a wearable heart rate sensor. Vehicle movement and heart rate were synchronized every 10 s. The subjects' average heart rates ranged from 69.09 to 87.63 bpm, which was higher than when traveling on paved forest roads. The physiological workload, based on %HRR *results, was greater during reverse travel, possibly due to blind spots and road obstacles such as roots or branches. Additionally,* %HRR *increases with travel speed during forward travel; however, the* %HRR *remained high even at low speeds during reverse travel. Furthermore, forward travel tends to keep the vehicle level, whereas reverse travel involves bumps due to sudden operational changes. It is crucial to enhance machine performance and structure in the future to reduce workload, improve visibility, and minimize blind spots.*

Keywords: driving vehicles, labor burden, heart rate, inertial measurement unit, travel speed, tilt angle

1. Introduction

Forestry is a hazardous occupation that results in numerous accidents and fatalities globally each year (Arman et al. 2022, Camargo et al. 2022, Lee et al. 2022). In Japan, forestry has the highest annual casualty rate among all industries (24.7 per 1000 workers), which is more than 10 times the annual average of 2.7 (Forestry Agency 2023a). Despite this, the supply of domestic timber has increased in recent years as imported timber prices have skyrocketed. In fact, the timber self-sufficiency rate in Japan has recovered to 41.1% (Forestry Agency 2023a). The number of forwarders used to transport timber has also increased annually to a total of 2863 units in 2021, which accounts for one-quarter of all forestry machinery in Japan (Forestry Agency 2023b). In addition, forestry road systems, including paved and unpaved forestry roads, reached a total length of 410,000 km in FY2021 (Forestry Agency 2023a). Forwarders must travel longer and longer distances as more forestry roads are built, which has caused the number of forwarder accidents to increase continually. Thus, the development of safer working environments is critical for the future development of the forestry industry.

Occupational accidents during forwarder-facilitated timber transportation can easily lead to serious incidents, such as falling off the road or tipping over (Imatomi et al. 2011, Kumazawa et al. 2011). Between 2003 and 2021, 19 fatal accidents occurred in Japan due to fallen or tipped over forwarders (Forestry and

Timber Manufacturing Safety & Health Association 2023). In Japan, forwarders often drive on narrow, unpaved, sloped roads that have a width of three to four meters, which increases the risk of falling or tipping if the driver is late in detecting and avoiding danger. Additionally, the operator is exposed to seat vibrations due to bumpy road surfaces and loud noises in forwarders without a cabin, which places a heavy labor burden on the operator (Camargo et al. 2022, Park et al. 2004). Phairah et al. (2016) concluded that the risk of worker musculoskeletal disorders (WMSDs) is increased by the unnatural posture of the head required to ensure adequate vision during forwarder work. The accumulation of these burdens leads to distracted driving that increases accident risk. Clarification is needed to better understand how vehicle movements and worker conditions place a heavy labor burden on forwarder drivers to develop more effective preventive measures against accidents caused by the increased labor burden.

Previous research on the working environment of forestry machinery operators (Arman et al. 2022, Camargo et al. 2022, Kymäläinen et al. 2023, Nakata et al. 2023a) and forwarders (Mozuna et al. 2016, Park et al. 2004, Usui 2021) has been conducted worldwide. For example, forwarder research has focused on mechanical (Mozuna et al. 2016, Usui 2021) and ergonomic approaches (Camargo et al. 2022, Park et al. 2004). Mozuna et al. (2016) developed a remote control technology that supports operation by memorizing driving operations, while Usui (2021) developed a road surface detection technology using deep learning and image data of the road network. The physiological burden on forwarder operators caused by vibration and noise during work (Camargo et al. 2022, Park et al. 2004) and the shape of forest roads (Iwakawa et al. 1977) have also been evaluated. Questionnaires (Arman et al. 2022), heart rate (Çalıskan and Çaglar 2010, Lee et al. 2022), and musculoskeletal disorders (Phairah et al. 2016) have been used as indicators. Park et al. (2004) conducted a test using a shaker to simulate off-road driving and found that the physiological load increases during continuous driving of more than 30 min and is dependent on road conditions. Furthermore, the visual demands of a driver's forwarding task may lead to an extreme head posture and the risk of WMSDs (Phairah et al. 2016). Imatomi (1997) and Iwakawa et al. (1977) found that driving speed has the greatest influence on the driver's physiological burden when driving on forest roads; however, the relationship between physiological workload and vehicle movement was not clear. Since conventional experiments are limited to indoor mock tests, a local increase in heart rate due to sudden changes in road gradient or vehicle slippage (Nakata et al. 2023b) has not been measured. Additionally, the steep (>30° slope) and narrow forest roads in Japan, make it impossible for forwarders to turn around; thus they need to drive in reverse. However, the forwarder large blind spot and the smaller, less safe seat that the driver uses when driving in reverse (often without a seatbelt) makes this dangerous (Fig. 1). Thus, the difference in the characteristics between forward and reverse travel were analyzed as well.

Fig. 1 Forwarder large blind spots from the operator's working position. These blind spots, created by the vehicle itself, can lead to delayed hazard avoidance, resulting in an increased risk of accidents

The purpose of this study is to assess the workload involved in operating forwarders, by measuring heart rate changes and vehicle movement. The difference in physiological burden between moving forward and in reverse on an actual forest work road was also measured to see the effect of blind spot. Machine movement data was collected with an IMU, and synchronized with heart rate to determine the relationship between physiological workload and vehicle movement.

2. Materials and Methods

2.1 Driving Tests

The driving tests were conducted from July 20th to 22th, 2022 at the Forestry Mechanization Center, Ministry of Agriculture, Forestry and Fisheries in Gunma Prefecture, Japan (36° 35′ 59″ N, 139° 14′ 44″ E). The subjects were tested two times with empty loads; first driving forward, then driving in reverse. The test was completed when the driver returned to the starting point. Fig. 2 shows elevation changes in the driving course based on vehicle movements. The maximum elevation difference was >50 m. The total course distance was approximately 1.8 km, starting from the dirt field and returning to the starting point via main and branch forestry operational roads.

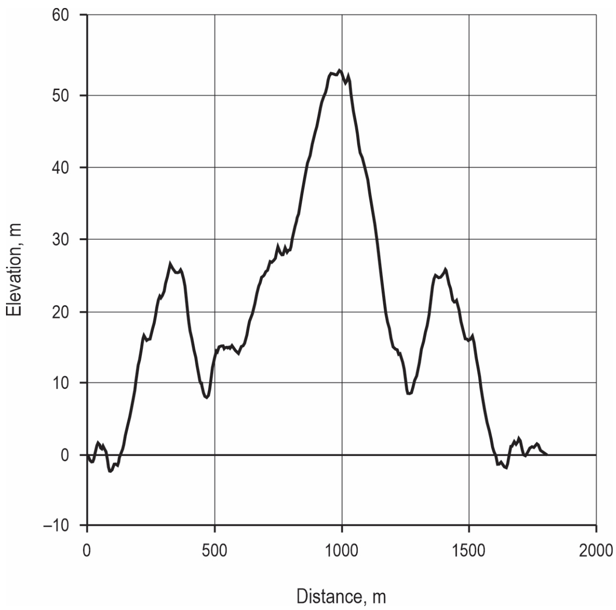

Fig. 2 Elevation changes in the driving course used in this study, with a total distance of 1.8 km

The average temperature (humidity) during the test was 29°C (55%) on the 20th, 29°C (41%) on the 21st, and 29°C (68%) on the 22nd in Gunma prefecture, Japan. The forwarder was an MST-650 with a VDLIII grapple (Morooka, Co.) with a maximum load capacity of 3.5 t. The running speeds ranged from »0 km/h« to »8 km/h« (low) and »0 km/h« to »11 km/h« (high; Fig. 3). This forwarder is a medium-sized vehicle widely used in Japan (Kumazawa et al. 2011).

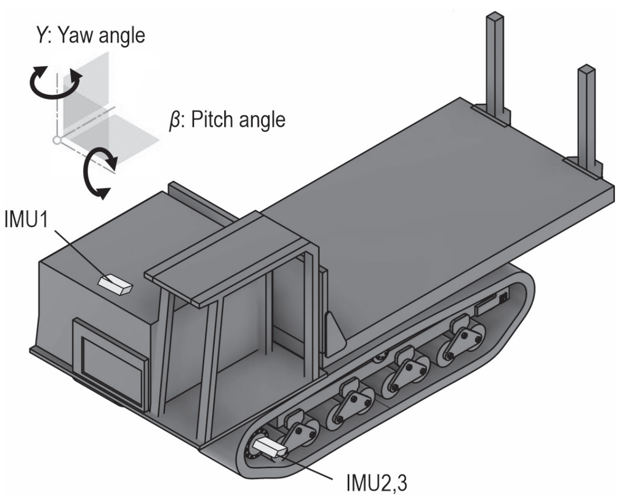

Fig. 3 Forwarder (MST-650 with VHDL grapple, Morooka Co.). The measurement device (NGIMU, x-io Technologies Ltd.) was attached to the front of the vehicle (IMU1), and the left (IMU2) and right (IMU3) sprockets

2.2 Subjects

This study was conducted with the approval of the Ethics Review Committee of the Forestry and Forest Products Research Institute, National Forestry Research and Development Agency. The subjects were informed about the purpose and procedure of the study and provided oral and written consent before participation. The subjects were five instructors from the Forestry Mechanization Center of the Forestry Agency's Forestry Technology Training Institute. The subjects use a forwarder mainly for training and education purposes. The subjects were all males aged 35–53 years, with 1–13 years of experience in operating forwarders (Table 1).

Table 1 Subjects

Subject	Gender	Age, years	Experience, years	Height, cm
1	Male	35	4	167
2	Male	51	13	179
3	Male	53	1	163
4	Male	40	3	163
5	Male	47	6	180

2.3 Measurement Method

In recent years, measurement sensors have been developed that make it easier to acquire various data outdoors (Jaatela et al. 2023, Nagy and Szalai 2023, Rietveld et al. 2023). For example, the inertial measurement unit (IMU) is a useful tool for estimating movements according to positions in a three-dimensional space. The IMU device is small, light, and easy to install on a vehicle; thus, it can measure various vehicle movements. Various fields of study have used IMUs, such as sports science, medicine, and robotics (Jaatela et al. 2023, Nagy and Szalai 2023, Rietveld et al. 2023). For example, movements made while walking (Jaatela et al. 2023) and playing sports (Rietveld et al. 2023) have been researched by measuring posture. Vehicle condition has also been estimated using its own movements and vibrations (Nagy and Szalai 2023). These sensors can log data without a communication device, which allows vehicle movement to be gauged more accurately than is possible with GPS or GNSS, even under a forest canopy with poor communication capabilities. In addition, the heart rate sensor has been miniaturized. For example, wristwatch-type sensors can be easily worn outdoors and create little hindrance to forestry work (Lee et al. 2022, Nakata et al. 2023b). Furthermore, conventional methods made analysis difficult to perform, since the assessments were based on visual observations and video images. If work content can be estimated from machine movements, then the time and effort spent on measurement can be saved and the number of subjects and amount of data can be increased.

2.3.1 Vehicle Movement

The movement of the forwarder was measured using three IMU (NGIMU; x-io Technologies Ltd.) devices (Fig. 1). The device weighed 45 g; thus, its effect on the study was negligible. One was attached to the front of the vehicle (IMU1) to obtain the tilt angle of the vehicle to monitor shaking. The other two were attached to the left (IMU2) and right (IMU3) sprockets to obtain the rotation speeds. The sprockets rotate the crawler and can be used to estimate the vehicle travel distance. Vehicle movement was logged at 50 Hz.

The moving distance of the sprockets was calculated using Eqs. 1–4. The parameters used in these equations are described in Fig. 4. The grouser pitch of the forwarder used in this study was 0.1 m and the number of sprocket teeth was 17.

$$L = \Delta\alpha_{sp} \times p \times n / 360 \tag{1}$$

$$\Delta\alpha_{spt+1} = \alpha_{spt+1} - \alpha_{spt} + 360 \quad \alpha_{spi+1} - \alpha_{spi} \leq -180 \tag{2}$$

$$\Delta\alpha_{spt+1} = \alpha_{spt+1} - \alpha_{spt} \quad -180 < \alpha_{spi+1} - \alpha_{spi} < 180 \tag{3}$$

$$\Delta\alpha_{spt+1} = \alpha_{spt+1} - \alpha_{spt} - 360 \quad \alpha_{spi+1} - \alpha_{spi} \geq 180 \tag{4}$$

Where:

L moving distance, m
α_{sp} roll angle of sprockets (roll angle of IMU2/IMU3), deg
p grouser pitch, m
n number of sprocket teeth
t elapsed time from the first sampling, s.

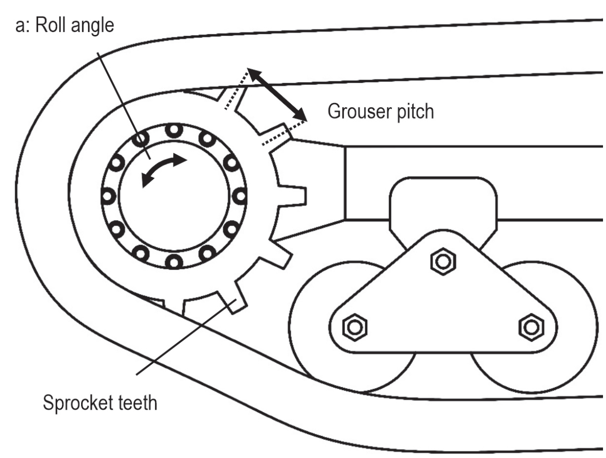

Fig. 4 Parameters of sprocket movements measured by IMU2 and IMU3

The traveling distance of the forwarder was calculated using Eqs. 5–7. The moving distance of both the left and the right sprocket was calculated using Eqs. 1–4. To estimate the travel distance, the moving distance was transformed into coordinates and projected onto a horizontal plane. The pitch angle of the vehicle was measured by the roll angle of the IMU device for convenience of measurement.

$$L_{avg} = \frac{L_{Li} + L_{Ri}}{2} \tag{5}$$

$$D_{Li} = L_{avg} \times \cos(RADIANS(\beta)) \times \cos(RADIANS(\gamma)) \tag{6}$$

$$D_{Ri} = L_{avg} \times \cos(RADIANS(\beta)) \times \sin(RADIANS(\gamma)) \tag{7}$$

Where:

L_{avg} moving distance of the vehicle center, m
L_{Li} moving distance of the left sprocket, m
L_{Ri} moving distance of the right sprocket, m
D_{Li} travel distance of the left sprocket, m
D_{Ri} travel distance of the right sprocket, m
β pitch angle of the vehicle (roll angle of IMU1), deg
γ yaw angle of the vehicle (yaw angle of IMU1), deg.

The total driving distance of the forwarder from the start point to the end point was calculated using Eq. 8.

$$D_{total} = \sum_{i=1}^{N} \sqrt{L_{Li}^2 + L_{Ri}^2} \tag{8}$$

Where:

D_{total} travel distance, m
N total number of samplings
i sampling number.

The travel speed of the forwarder was calculated by Eq. 9.

$$V_i = \frac{\sqrt{L_{Li}^2 + L_{Ri}^2}}{t_{i+1} - t_i} \times 3.6 \tag{9}$$

Where:

V travel speed, km/h.

The tilt angle of the forwarder (i.e., the pitch angle of the vehicle (deg)), was measured using the roll angle (deg) of IMU1.

The turning speed was calculated by Eq. 10.

$$\omega = \frac{\beta_{i+1} - \beta_i}{t_{i+1} - t_i} \tag{10}$$

Where:

ω turning speed (deg/s).

2.3.2 Physiological Workload

Physiological workload was assessed using heart rates, which were measured using wearable sensors (myBeat, Union Tool Co.) attached to a chest strap that obtained heart rate via electrocardiography. Heart rate is the reciprocal of R–R intervals (i.e., R-wave peak to R-wave peak in electrocardiograms) per beat interval (Peng et al. 2021). For calculations of physiological workload, the relative heart rate at work (*%HRR*) was determined using Eq. 11 (Çalıskan and Çaglar 2010, Lee et al. 2022). Resting heart rate was measured during rest times before and after the driving tests.

$$\%HRR = \frac{HR_{\text{work}} - HR_{\text{rest}}}{HR_{\max} - HR_{\text{rest}}} \times 100 \quad (11)$$

Where:

%HRR relative heart rate

HR_{work} average heart rate during work

HR_{rest} resting heart rate

HR_{max} maximum heart rate (220 – worker age).

2.4 Data Analysis

Heart rate and vehicle movement data were synchronized over time to analyze their relationship. Since the sampling intervals differed in these two measurements, average values were calculated every 10 s for both data sets and then synchronized. Ten seconds allows for less data loss and maintains the data characteristics. The mean heart rate of the forward and reverse data sets were compared using Welch's two-sample test. The software program R v4.2.1 was used for statistical analysis

3. Results

A summary of the results is shown in Table 2. Table 3 shows differences between forward and reverse travel. *N* represents the total count of sampling data calculated every 10 seconds during driving test.

3.1 Heart Rate and %HRR

The mean heart rates ±*SD* of all subjects was 79.79±8.68 bpm. The minimum value was 57.12 bpm, and the maximum value was 112.93 bpm. The subjects' mean heart rates ±*SD* were 82.02±8.39 bpm (Subject 1), 79.70±5.24 bpm (Subject 2), 78.61±7.62 bpm (Subject 3), 87.63±5.48 bpm (Subject 4), 69.09±4.04 bpm (Subject 5; Table 2).

The mean *%HRR* ±*SD* of all subjects was 7.68±4.83. The minimum value was 0.00, and the maximum

Table 2 Summary of results

Subject	*N*		*HR*, bpm	*%HRR*	Travel speed, km/h	Tilt angle, dog	Turning speed, dug/s
1	258	*M*	82.02	13.52	5.03	2.20	0.08
		SD	8.39	4.54	1.25	8.29	7.32
		Min.	57.12	0.07	1.06	–17.37	–35.28
		Max.	112.93	30.23	7.96	22.31	33.61
2	242	*M*	79.70	6.92	5.36	2.89	–0.05
		SD	5.24	3.12	1.73	7.77	8.36
		Min.	68.55	0.32	1.09	–15.47	–34.87
		Max.	106.47	22.76	9.27	20.01	34.35
3	288	*M*	78.61	6.38	3.87	1.15	0.00
		SD	7.62	4.57	0.96	7.97	6.86
		Min.	68.00	0.00	1.00	–18.44	–35.80
		Max.	105.33	22.36	5.98	16.88	36.36
4	267	*M*	87.63	7.02	4.36	–0.36	0.06
		SD	5.48	3.04	1.41	8.60	7.67
		Min.	75.58	0.32	0.04	–19.45	–35.02
		Max.	109.65	19.25	6.61	18.51	37.01
5	216	*M*	69.09	4.10	5.91	–0.42	0.13
		SD	4.04	2.34	1.28	8.79	4.85
		Min.	62.64	0.37	1.24	–18.56	–20.24
		Max.	98.56	21.13	9.34	19.66	30.54

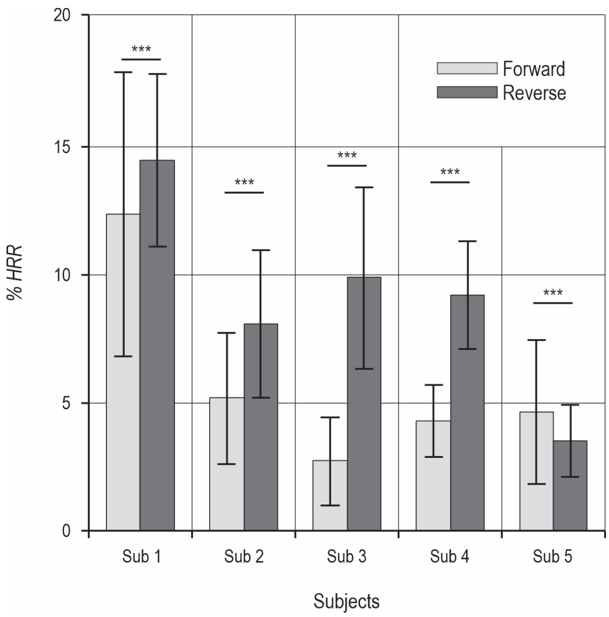

Fig. 5 Subject's *%HRR* during forward and reverse travel. The heart rate means during forward and reverse travel were compared using Welch's two-sample tests (*** $p<0.001$; *t*-test)

value was 30.23. The subjects' mean *%HRR* ±*SD* were 13.52±4.54 (Subject 1), 6.92±3.12 (Subject 2), 6.38±4.57 (Subject 3), 7.02±3.04 (Subject 4); 4.10±2.34 (Subject 5; Table 2).

The mean value of *%HRR* during forward and reverse travel ranged from 2.69 to 12.30 and 3.44 to 14.42, respectively (Table 3). The mean value of *%HRR* (i.e., *mean*±*SD*) during forward (reverse) travel in subjects 1–5 was 12.30±5.56 (14.42±3.38), 5.13±2.58 (8.04±2.89), 2.69±1.77 (9.83±3.57), 4.26±1.43 (9.15±2.09), and 4.61±2.78 (3.44±1.38), respectively (Table 3).

3.2 Travel Speeds

The mean travel speed ±*SD* of all subjects was 4.84±1.52 km/h (Table 2). The minimum value was 0.04 km/h, and the maximum value was 9.34 km/h. The mean value of travel speed during forward and reverse travel ranged from 4.46 km/h to 6.91 km/h and 3.31 km/h to 6.69 km/h, respectively (Table 3). With the exception of Subject 5, the subjects' travel speed was greater in forward than in reverse travel.

Fig. 6 shows the travel speed and *%HRR* of all subjects in forward and reverse travel. The vertical axis

Table 3 Differences between forward and reverse travel

Subject	N		*%HRR* Forward	Reverse	Travel speed, km/h Forward	Reverse	Tilt angle, dog Forward	Reverse	Turning speed, deg/s Forward	Reverse
1	258	*M*	12.30	14.42	5.96	4.35	–1.18	4.67	–0.16	0.26
		SD	5.56	3.38	1.18	0.77	7.50	7.99	5.43	8.46
		Min.	0.07	8.16	1.06	1.81	–17.37	–11.58	–27.37	–35.28
		Max.	30.23	27.43	7.96	5.85	12.71	22.31	26.45	33.61
2	242	*M*	5.13	8.04	6.91	4.39	1.49	3.77	–0.16	0.03
		SD	2.58	2.89	1.56	0.96	7.55	7.81	5.48	9.75
		Min.	0.32	1.92	1.21	1.09	–15.47	–12.57	–12.03	–34.87
		Max.	22.68	22.76	9.27	7.83	15.51	20.01	32.04	34.35
3	288	*M*	2.69	9.83	4.46	3.31	–0.14	2.35	–0.15	0.13
		SD	1.77	3.57	0.73	0.82	7.62	8.13	5.89	7.67
		Min.	0.00	3.19	1.00	1.03	–18.44	–15.37	–34.06	–35.80
		Max.	12.57	22.36	5.98	4.60	15.54	16.88	33.53	36.36
4	267	*M*	4.26	9.15	5.39	3.55	1.50	–1.82	–0.07	0.16
		SD	1.43	2.09	1.10	1.08	8.31	8.57	6.24	8.64
		Min.	0.32	4.92	0.04	0.12	–15.48	–19.45	–29.22	–35.02
		Max.	7.81	19.25	6.61	5.46	18.51	15.35	33.86	37.01
5	216	*M*	4.61	3.44	5.30	6.69	–4.38	4.62	0.08	0.20
		SD	2.78	1.38	0.80	1.36	7.50	7.70	4.51	5.27
		Min.	0.42	0.37	1.24	1.49	–18.56	–11.30	–15.11	–20.24
		Max.	21.13	6.50	6.49	9.34	11.74	19.66	30.54	28.91

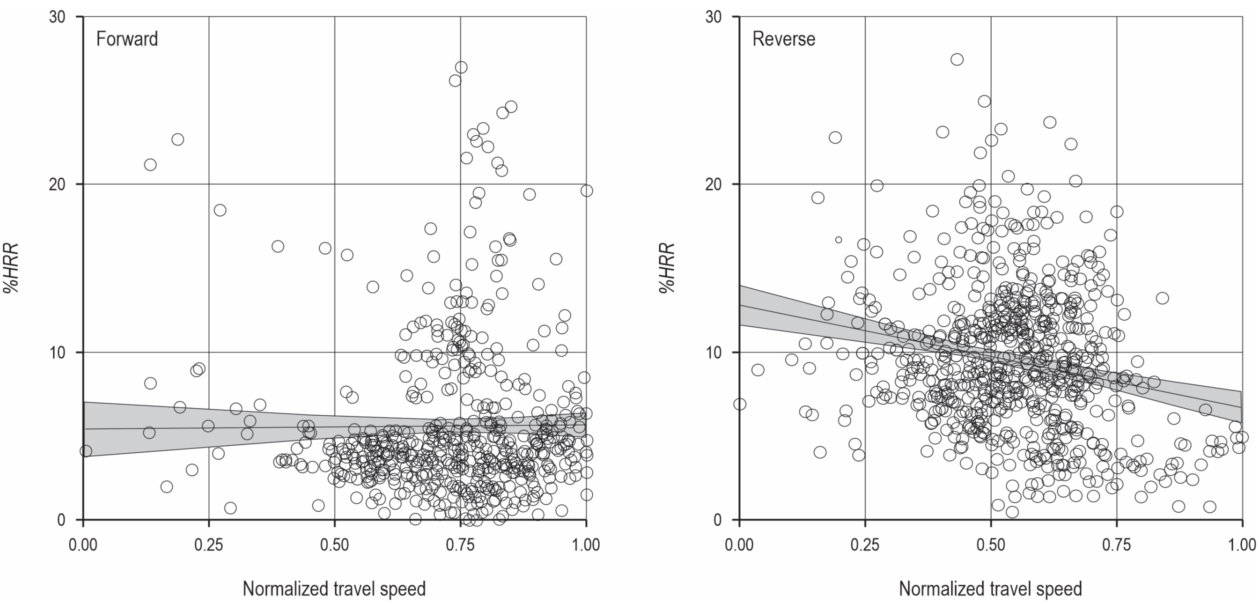

Fig. 6 Normalized travel speed and *%HRR* of all subjects during forward and reverse travel. Normalized travel speed was divided by the maximum travel speed of each subject. The black line shows the relationship between travel speed and *%HRR*. The grey area shows the 95% confidence interval

displays *%HRR* and the horizontal axis provides the normalized travel speed divided by the maximum travel speed of each subject. Forward travel had many points distributed at high travel speeds and the *%HRR* tended to increase when the normalized speed exceeded 0.5 of the maximum speed. In particular, when the normalized speed exceeded 0.75, the *%HRR* ranged from 20–30. In reverse travel, many points were distributed at low travel speeds and many plots had high *%HRR* values between 0.25 and 0.75 normalized speeds. In addition, when the normalized speed was 0.75 or more, the *%HRR* was distributed at a low point of 5 or less.

3.3 Tilt Angle

The mean ±*SD* of the longitudinal tilt of all subjects' vehicle in the sagittal plane was 1.11±8.37°. The minimum value was −19.45°, and the maximum value was 22.31° (Table 2). The mean value of tilt angle during forward and reverse travel of all subjects ranged from −4.38° to 1.50° and −1.82° to 4.67°, respectively (Table 3). Except for Subject 4, all subjects had a larger mean tilt angle during reverse travel that was distributed more toward the positive side. The *SD* value of tilt angle during forward and reverse travel of all subjects ranged from 7.50° to 8.31° and 7.70° to 8.57°, respectively (Table 3).

Fig. 7 shows the results of tilt angles of the vehicle during forward and reverse travel for the subjects

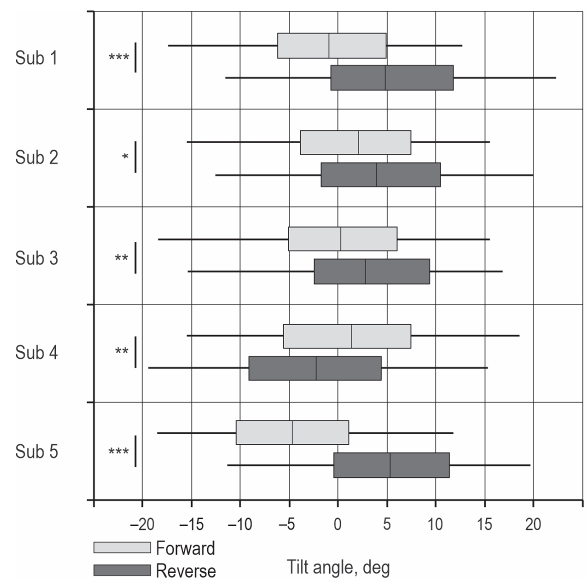

Fig. 7 Tilt angle of all subjects during forward and reverse travel. The light grey boxes show the forward travel, and the dark grey boxes show reverse travel. The tilt angle means in forward and reverse travel were compared using Welch's two-sample tests (*** $p<0.001$; ** $p<0.01$; * $p<0.05$; *t*-test). The line inside the box represents the median of the dataset. The box represents the interquartile range (IQR), indicating the range between the first and the third quartile. The lines (whiskers) extending above and below the box indicate the overall range of the data, with a consistent distance (1.5 times the IQR) from the third quartile and the first quartile, respectively. Data points outside the whiskers represent outliers beyond this range

using a box plot. The average values of the tilt Angle during forward and reverse travel were significantly different for all subjects (p<0.001, p<0.01, p<0.05, t-test).

In this study, all participants (except for Subject 4) exhibited larger tilt angles during reverse travel, and the tilt angles were distributed on the positive side in reverse travel (Fig. 7).

3.4 Turning Speed

The mean ±*SD* of the turning speed of all subjects' vehicle was 0.04 deg/s ±7.14 deg/s. The minimum value was –35.80 deg/s, and the maximum value was 37.01 deg/s (Table 2). The mean value of turning speed during forward and reverse travel of all subjects ranged from −0.16 deg/s to 0.08 deg/s and 0.03 deg/s to 0.26 deg/s, respectively (Table 3). In addition, the minimum and maximum values of the turning speed during forward travel were as follows: minimum, –34.06 – –12.03 deg/s; maximum, 26.45 – 33.86 deg/s (Table 3). The minimum and maximum values of the turning speed during reverse travel were as follows: minimum, –35.80 – –20.24 deg/s; maximum, 28.91 – 37.01 deg/s (Table 3). In all subjects, reverse travel had a larger minimum–maximum range value and *SD* compared to forward travel. No significant differences were observed in the mean turning speed values between forward and reverse travel (p>0.05, t-test, Fig. 8); however, it is noteworthy that more outliers were observed in the plots of reverse travel.

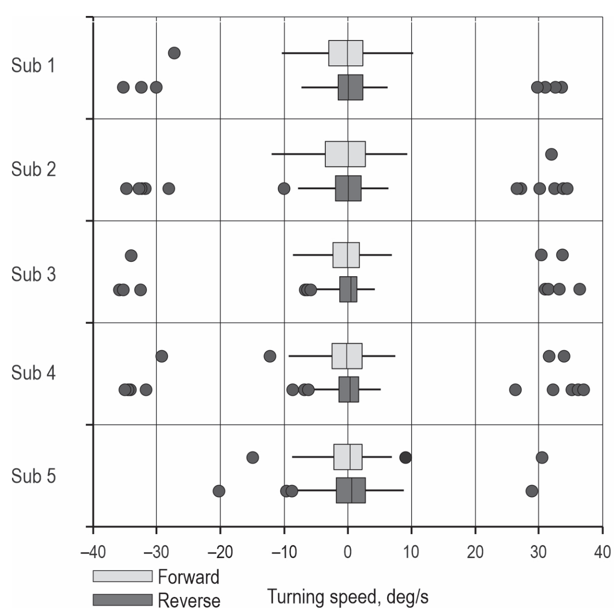

Fig. 8 Turning speed of all subjects during forward and reverse travel. Light grey boxes show the forward travel, and dark grey boxes show reverse travel

4. Discussion

4.1 Physiological Workload in Operating Forwarders

4.1.1 Heart Rate

An increase in heart rate while driving is an indicator of mental workload (Paxion et al. 2014). In this study, the subjects' average heart rates ranged from 69.09 to 87.63 bpm. This was higher than when traveling on paved forest roads (*mean* 71.8 bpm; *range* of 67.3 – *maximum* 78.0 bpm; Yamazaki 1987), but lower than values obtained during actual forwarder operation at a worksite, including loading work (86.8 bpm, *maximum* 136 bpm; Inoue and Kobayashi 1996). This finding is attributed to factors such as work urgency and coordination with other tasks. In addition, physiological workload increases when driving a loaded vehicle (Yamazaki 1987). Since this study was conducted without a load, it is presumed that the heart rate was relatively lower.

4.1.2 %*HRR*

The forwarder operator workload while sitting was not as high as that of other forestry works (Yamazaki 1987); however, there were participants with %*HRR* exceeding 30, indicating a workload similar to walking (%*HRR* is 28.33; Yamazaki 1987). According to Çalskan and Çaglar (2010), a %*HRR* up to 10 is classified as resting, while up to 20 is very light work, and up to 30 is moderate work. The workload in this study was mostly categorized as resting and very light work, but sometimes included moderate work.

Moreover, driving posture can increase physiological stress (Bridger 2008, Phairah et al. 2016, Qu et al. 2012). Particularly when driving a forwarder, operators need to change their posture significantly, such as leaning out of the cabin to check the roadside and obstacles (Phairah et al. 2016). The average subjects' %*HRR* in this study ranged from 2.69 to 12.30 during forward travel and from 3.44 to 14.42 during reverse travel. The higher workload during reverse travel may be caused by blind spots due to the machine itself. Even during forward travel, the roadside on the opposite side of the driver's seat cannot be clearly seen. If the driver does not maintain a good posture to ensure visibility, workload can be increased. Additionally, in steep terrain such as Japan, the cabin itself may tilt, and drivers have difficulties maintaining a stable posture. Phairah et al. (2016) reported that prolonged work in extreme postures could pose a risk of WMSDs. Since the forwarder often runs for a long time, the risk of WMSDs increases with extended periods of extreme postures.

4.2 Vehicle Movements

In this study, the working conditions that affect the operator's workload were analyzed from the vehicle movement, such as travel speed (Imatomi 1997, Iwakawa et al. 1977), tilt angle (Masuda and Shiiba 2023, Zaidi et al. 2000), and turning speed which is thought to affect the vibration (Du et al. 2018, Kittusamy and Buchholz 2004).

4.2.1 Travel Speed

Travel speed is the most critical factor influencing the physiological workload of operators (Imatomi 1997, Iwakawa et al. 1977). In this study, the average travel speed of the subjects ranged from 3.87 to 5.91 km/h (Table 2), which was similar to the normal forwarder speeds reported in previous studies (Imatomi 1997, Kumazawa et al. 2011, Oka et al. 2007). Except for Subject 5, travel speeds were lower during reverse travel than forward travel (Table 3).

Imatomi (1997) reported that physiological stress rapidly increases as travel speed increases. Thus, it can be inferred that the workload is higher during forward travel due to the higher speed; however, in this study, the heart rate and %*HRR* were found to be higher during reverse travel (Table 3).

Therefore, forward and reverse travel were analyzed separately (Fig. 5). As a result, the workload (%*HRR*) increases as the travel speed increases during forward travel. On the other hand, during reverse travel, the %*HRR* tended to increase with increasing speed, however the %*HRR* remained high even at low speeds during reverse travel. According to Imatomi (1997), physiological stress does not necessarily decrease at low speeds when obstacles such as roots or branches are present. This might cause a high physiological workload at low speeds. It is crucial to improve machine performance and structure in the future to reduce the workload, enhance visibility, and reduce blind spots.

In addition, travel speed changes depending on curve radius and slope (Oka et al. 2007), so these effects should be investigated in future.

4.2.2 Tilt Angle

Tilt angle is one of the factors affecting the car riding comfort (Masuda and Shiiba 2023). Moreover, as the operator's posture and head orientation were poor because of the vehicle tilt angle, the labor burden tends to increase. Zaidi et al. (2000) reported that head up tilt of 45–90° produced progressive increases in heart rate of 10–20%. Kittusamy and Buchholz (2004) reported that operators of constructions exposed to awkward postural demands have risk factors leading to health problems. In this study, the tilt angle was about ±20°, suggesting that the awkward head up tilt and posture during operation were not good, causing physiological workload.

In addition, when the vehicle moves up and forward with respect to the direction of travel, it is difficult to see the road surface and to grasp the situation. Hill and Boyle (2007) reported that people with an experience of accidents were more likely to be stressed by poor visibility while driving. According to Nakata et al. (2023a), most log truck drivers experience near-misses while driving on forest roads. Considering that forwarder drivers operate on roads within forests, it is expected that forwarder drivers are also prone to stress. Furthermore, blind spots can lead to accidents if the driver delays avoiding danger. In fact, the inability to detect the shape of the road during reverse travel likely explains the observations of frequent brake use, which could contribute to the increased workload. Therefore, in order to reduce the workload and drive safely, it will be necessary to construct roads and to review the mechanical structure to secure visibility.

Comparing a forward travel and a reverse travel, the *SD* values for all subjects were slightly higher for reverse travel, which suggests that the vehicle was more prone to instability, such as shaking and bumping. This indicates that the vehicle was often in a nose-up position during reverse travel. All participants (except for Subject 4) exhibited larger tilt angles during reverse travel, and the tilt angles were distributed on the positive side in reverse travel (Fig. 7). The nose-up position commonly occurs when applying brakes; thus, it can be inferred that there was frequent brake use during reverse travel.

Furthermore, in this study, participants followed the same course and returned to the same location to eliminate the effect of terrain variation on the results. In addition, in this test, tilt angle was measured every 10 s to see the relationship with the heart rate, but if the tilt angle was analyzed in a shorter time, the vehicle movements due to the unevenness of the road surface would be understood, and the physiological workload caused by it would be elucidated.

4.2.3 Turning Speed

When the turning speed is high, the machine will move roughly, and the vibration will also be large. In this test, turning speed was used as an index to grasp the smoothness of the running and the vibration caused by it. Operators of construction and agricultural machinery have been found to be adversely affected by prolonged vibrations (Du et al. 2018, Kittusamy and Buchholz 2004), and the same can happen with forestry machinery. All participants had a larger *minimum-maximum* value range and *SD* value for turning speed during reverse travel compared to forward travel (Table 3). There were also more plots indicating outliners during reverse travel (Fig. 6). This indicates that reverse travel often involves rough driving in contrast to the smooth motion exhibited during forward travel. In addition, the increased variability in turning speed during reverse travel despite lower travel speeds implies frequent abrupt changes in maneuvers and was likely influenced by unexpected obstacles or road conditions. If the machine could be operated smoothly in reverse and vibration could be reduced, the driver's discomfort would be reduced, and it would be easy for the driver to remain vigilant, which would lead to improved health and a reduced risk of accidents.

5. Conclusions

The results of this study reveal that the subjects' heart rates were higher than when traveling on paved forest roads. The forwarder operator workload while sitting was not as high as that of other forestry works; however, *%HRR* indicated a workload similar to walking. Additionally, the risk of health problems increases with extended periods of awkward postures to ensure visibility due to blind spots. In addition, considering the difference in workload between forward and reverse travel, our results show the following:

⇒ the workload increases as the travel speed increases during forward travel, while the workload remains high even at low speeds during reverse travel. This might be attributed to the need for vigilant driving because of obstacles, due to the large blind spots during reverse travel

⇒ the result of tilt angle suggests that the awkward head up tilt and posture cause physiological workload. Furthermore, it is deduced that the vehicle moves up and forward with respect to the travel direction during reverse travel, making it difficult to see the road surface and grasp the situation

⇒ the result of turning speed indicates that the reverse travel often involves rough driving in contrast to the smooth motion during forward travel.

From these findings, reducing physiological burden would necessitate introducing safety equipment to assist in enhancing the visibility, along with ensuring adequate road width for safe driving. Different situations should be considered in future studies, such as vehicles loaded with different centers of gravity, and shorter time span to capture acceleration or monitor shaking and bumping.

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