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Heart Rate Index as a Measure of Physical Workload in Chainsaw Operations

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Abstract: Timber harvesting operations, including manual and motor-manual activities, require workers who are in good health to be able to work effectively. The aim of our paper was to introduce a simplified index methodology for workload assessment. Generally available wearable technology, namely Garmin, Biostrap, and Whoop devices, were used. The dependence of the heart rate (HR) on physical workload was examined to calculate the Heart Rate Index. The case study was performed with several variations of chainsaw devices cutting the poplar wood. It was proved that the use of a heavier work tool, MS 500i/90 cm 9.3 kg, contributes both to the creation of a non-ergonomic working position and to an increase in the energy required to perform work, which was represented by an increase in heart rate. With a lighter work tool and a shorter cutting blade, both a decrease in heart rate and a reduction in the working time performed in a non-ergonomic position were achieved. The results can be used in common practice for workers' self-assessment to increase safety and health protection at work or work productivity, not only in forestry-related professions.

Keywords: tree processing; ergonomics; wearable technology; energy consumption; occupational health; forestry safety

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1. Introduction

Work in timber harvesting operations, including tree felling and processing, is considered to be a heavy job with a specific level of safety hazards and harmful factors. Workers are influenced by many personal factors, as well as external conditions [1–3]. Motor-manual fellers are exposed to extreme temperatures [4], and they cover long distances during work or in difficult terrain, which can cause physical strain [5]. Other harmful factors that are often investigated are noise or vibrations [3], increased risk of musculoskeletal disorders due to work postures [6–9], vascular disorders [10], or even disobeying safety procedures [11,12]. Workers in logging and forest environments during their working activities may be exposed to various hazards and risks. The physical workload during manual activities in logging and forest environments is extremely high [13,14]. Forest workers during a long-time working activity may work with excessive demands beyond their physical abilities. For proper safety, long-term overload, and injury protection, it is important to evaluate and analyze the real impact of the working activities and potential workload danger and risks [10].

Based on analytical knowledge, we analyzed workload danger and risks in a workload model that includes the physical characteristics of workers, including body heart rate measurement. We expected that current measurement and wearable devices have sufficient performance for measuring biological and physical load data without disturbing the work of the observed people [15,16].

Theoretical Background

From the point of view of the ergonomics of work activity, work performance is influenced by a number of external conditions, work environments, or circumstances of work performance. External factors and readiness for work performance influence the physiological and psychological state of the worker and his overall work performance. Work activity is always a burden for the organism, the size of which depends mainly on the physical and psychological state of the worker, the ability to prepare for the performance of a specific work activity in the given conditions, and the work activity itself that is being performed. To assess the workload, we took into account also the fact that the ability and performance of workers change in the long term with gender and age, but especially in the short term of the body's physiology, there are changes in readiness for performance during the day [17–21]. The highest workload on the organism is in the morning and mid-morning hours between 7 and 12 o'clock. Between 1 and 3 p.m., there is a slight decrease in performance, and between 4 and 9 p.m., physiological performance remains at a stable level. Then, after 9 p.m., it decreases to a minimum level [1].

Environmental conditions, such as temperature, humidity, and altitude, may influence HR performance. Our study also measured and controlled these variables when the results were finalized. Nevertheless, for instance, heart rate (HR) indices in temperate forestry environments may differ from those in tropical regions due to varying thermoregulatory demands.

From the point of the organization of the workload, it is appropriate that the workload and the cycle of the imposed work pace correspond to the highest possible performance. If the mutual coordination of the physiology of performance and the ability of the organism to handle the load is not observed, the effects of the workload on the health of the employees may gradually begin to manifest. The impact of workload is related not only to the ability to cope with the current physical or mental load but also to the ability to regenerate between individual performances. The consequences of workload can then be divided into two parts: short-term, which disappear after the end of the work performance or during the recovery period after the performance and do not create functional irreversible changes or permanent consequences on the health of workers, and long-term, which persist even after the recovery period, and from a long-term perspective, they can cause functional, irreversible changes or the deterioration of workers' health [22–25].

During the performance of a work activity, the locomotor and cardiovascular apparatus are stressed. Other factors, such as metabolism, thermoregulation, fluid loss, and others, are also related to work performance. According to the intensity of the work activity and the effects of the surrounding environment, the burden on the organism can be divided into low, reasonable, excessive, and extreme.

For the evaluation of individual areas of stress, we must take into account its length, type, and intensity, as well as the basic physical and physiological prerequisites of the person performing the work activity. When determining the total physical load, we rely on the data of the basic metabolic values of the given person or group of people (basal metabolism), as well as on the energy expenditure during the performance of a specific work activity or a group of activities of a similar nature. From the point of view of the performance of one's work activity, we can also take into account the type of work activity—whether it is static or dynamic work. In static work, actions such as holding tools or objects for the performance of work activity or maintaining a working position for approximately 2–3 s and involving mostly small muscle groups are predominant. Dynamic work is primarily the performance of one's work without or with the use of tools over a longer period and involving mainly large muscle groups. Depending on these main physiological parameters, the body energy required for the performance of the work activity is consumed. The amount of energy consumed is also influenced by the working environment and conditions during the performance of work activities. From the point of the activities performed and the way the body is stressed during work activities, it is necessary to divide physical stress into local and general stress. In the case of local loads, specific body parts are loaded, such as parts of the upper or lower limbs or individual segments of the spine. For the total physical load, we considered the involvement of large muscle groups in a volume greater than 50% of the total muscle mass. From the point of view of body physiology, we can better determine both the energy demand of the work performed, as well as the physiological parameters related to the involvement of a large volume of muscle mass. Based on the aforementioned assumptions, we considered that with increasing energy demands, there is both greater energy consumption by muscle activity and greater strain on the cardiovascular and respiratory systems. The activity of the respiratory and cardiovascular systems and their selected indicators can be easily monitored and subsequently evaluated during overall physical work in a non-invasive manner. From the point of view of practical assessment of the total physical load of the activities performed, it is advantageous to use the expression of energy demand using heart rate values [26].

At present, non-invasive measurement of heart activity using various wearable devices appears to be the most suitable for monitoring and evaluating physiological parameters during the performance of work. These devices are capable of sensing heart activity/pulse with relatively high accuracy and also eliminate several artifacts arising during the measurement itself [25,27–32].

In work physiology, physical strain can be described as total body strain or local strain on specific body parts. Above all, large muscle groups need a large amount of oxygen to ensure movement and performance, which is why the respiratory and cardiovascular systems are strained in connection with the physiological movements of the muscles. From the point of view of the performance of work activities, the work performed can be divided into several areas: force work, work associated with static loads, manual handling, and repetitive work. Power work is work that primarily requires good stability of the human body, and in many cases, it is necessary that during this work, the muscles contract up to the areas of maximum voluntary contraction. Power work refers to the load of the whole body or its specific parts, such as pushing and pulling. With static load, the body as a whole or a part of the body is usually loaded with work in which the same position is maintained continuously for a long period of work, and individual muscles resist the required load during work. In many cases, there is also prolonged muscle tension or muscle activity without variation in muscle movement or stretching. For work associated with manual manipulation, in contrast to strength work and in addition to good body stability and the use of the strength of large muscle groups, it is necessary to emphasize the necessity of performing a specific load of small muscle groups of the upper limbs associated with grasping the manipulated object.

Repetitive work is created by requirements for repetitive cycles of production processes or work activities. Due to the variability of this work activity, there is currently no unified opinion on its definition. Repetitive work can be tied to the duration of the work cycle, the repeatability of work movements, or, for example, the repeatability of dynamic and static load during the performance of a work activity. According to statistics, the most used specifications are the task cycle duration of less than 30 s or the identification of the same movements, static or dynamic actions that are performed for more than half the time within one work cycle [22,24,25,33,34].

This article describes the practical application of the simplified heart index methodology for workload assessment and points out the use of this method.

2. Materials and Methods

2.1. Experimental Evaluation Tools

In our case study, heart rate and physical activity were measured using different wearable equipment with different biosensors. We measured working activities such as tree-cutting, delimbing, crosscutting, chocker-setting, manual axe chopping, and cutting with a chainsaw, including different cutting conditions using different bar lengths and cutting conditions.

For each working activity, we examined the dependence of the heart rate (HR—number of beats per minute) on physical workload. Biological parameters such as moving/walking pattern and HR were taken both when the worker was at quiet/rest time before work and continuously during work. Based on measured values, we counted the level of workloads. The level of the workloads was classified as ration values of the workload and rest HR. The counted final value is divided into different levels: very low, low, moderate, high, and very high load index.

$$I_{HR} = \frac{\text{HR load}}{\text{HR rest}} \tag{1}$$

If we investigate workload limit values of energy expenditure per work shift, there is 5.1 MJ (permitted max. 6.1 MJ) for women and 8.25 MJ (permitted 9.9 MJ) for men. To assess the shift load, it is also important to know the periods of rest periods, the frequency of movements, working positions, and workplace conditions [35,36].

Average heart rate values measured using the wearable devices Whoop, Biostrap, and Garmin were used for the case study. We tried to consider measurement rates/accuracy impact and how the measurements were taken.

Measurement rates and accuracy of devices are as follows:

1. Biostrap

Measurement Rate: Sample data were at up to 86 Hz for heart rate and other biometric readings.

Accuracy: It is equipped with clinical-grade PPG sensors using red and infrared light, offering superior accuracy for tracking oxygen saturation and heart rate variability (HRV). It performs well in tasks requiring stationary positions but is robust in mitigating motion artifacts.

2. Garmin Fenix 3 HR

Measurement Rate: Garmin HR 3 measures HR with two green LEDs 32 Hz sampling during standard use and higher rates and 256 Hz during activity tracking.

Accuracy: It employs green light PPG sensors, which are effective for measuring heart rate but may have reduced accuracy under motion or darker skin tones compared with red or infrared sensors.

3. Whoop

Measurement Rate: Whoop measures HR with five LEDs (three green, one red, and one infrared) 24/7 at a sampling rate of 100 times per second.

Accuracy: It utilizes red, green, and infrared light photoplethysmography (PPG) sensors, which provide reliable readings even during high-intensity motion. It is known for its high precision in tracking recovery metrics and strain levels.

2.2. Sensor Placement

- ○ Biostrap: Two sensors are worn on the forearm and upper arm, with options for placement on other areas like the upper arm, depending on the activity. Adjustments are made to optimize sensor contact and signal integrity and eliminate movement artifacts.
- ○ Garmin Fenix 3 HR: It is worn on the left wrist with the sensor flush against the skin. Placement is critical for avoiding interference from wrist movement during tasks.
- ○ Whoop: It is positioned on the right wrist, with guidance to ensure a snug fit without impeding circulation. Placement minimizes light leakage for consistent PPG readings.
- ○ The placement of the Whoop and Garmin sensors was taken based on the accuracy and ability of the sensors to avoid the artifacts. The selection of the Whoop placement on the right hand was taken as the reason that Whoop has a combination of green, red, and infrared sensors to avoid movement artifacts of the forearm and wrist movement during the moto manual activity.

2.3. Data Collection and Data Processing

Data Collection Protocol:

Baseline Calibration: This was conducted at the start of this study to establish good measurement points and measure for a minimum of 5 min without movement. With the

Biostrap and Woop, the calibration sequence was also combined with the basement HRV resting measurement for each device.

Task-Specific Recording:

Each device was recorded continuously during active tasks, capturing heart rate and activity data. Data were synchronized to a universal time clock to facilitate alignment across devices.

Environmental Control: Environmental factors (e.g., temperature, lighting) were controlled or recorded to account for their potential impact on sensor performance.

Data Processing:

Measured data from all three devices were time-coded globally for synchronization and possible further processing. Each device supports cloud or app-based synchronization, enabling the collection of large datasets for subsequent analysis. Data from all devices were processed firstly in the individual apps, and then some of the data were exported to standardized formats such as CSV for additional processing.

This systematic approach ensured reliable measurement, accurate synchronization, and meaningful analysis of physiological metrics across given tasks.

Based on the results of the practical testing of the wearable devices and the results of the below-mentioned studies, we decided, in these kinds of work and performance activities, not to take into account possible device inaccuracy or impact of the artifacts. The studies [37,38] proved that the results of most of the current wearables fit the needs of the application.

Multi-Factor Analysis: Other factors that might influence worker performance and recovery, such as nutrition, sleep, and mental stress, were explored. We limited the evaluation of the Multi-Factor Analysis to the week before the experiment and the week after the experiment. Those analyses were not the subject of the experiment evaluation. We tried only to evaluate the functional validity of the subject of this study.

2.4. Justification of Selected Wearables

The reasons for using Garmin, Biostrap, and Whoop are primarily based on the following groups of parameters:

As for users, all three devices have been used in practice for a long time to measure various parameters of exercise and exercise capacity. The devices are commercially manufactured, certified, and globally available to users. Their manufacturers provide full support and service to users. User interfaces are easy to use.

As for measurement and data collection, all three devices used are, in principle, capable of measuring heart rate information with high accuracy both at rest and in motion; the combined use of green, red, and IR light sources is in the individual devices linked to their optimal placements. The Whoop and Garmin devices are placed on the wrist for measurement purposes; the Biostrap device is placed on the arm or forearm to potentially eliminate unwanted influences and measurement artifacts caused by grip, large grip, and dynamic wrist movements. The devices capture the heart rate signal at a relatively high sampling rate: Garmin HR 3 measures HR with two green LEDs 256/32 Hz sampling; WHOOP measures HR with five LEDs (three green, one red, and one infrared) 24/7 at a sampling rate of 100 times per second; and Biostrap measures HR with three green LEDs 24/7 at a sampling rate of 86 times per second.

As for data collection, Whoop is known for advanced recovery and strain analysis, utilizing a red-light PPG sensor for improved accuracy during physical activity and varied conditions. Biostrap features a multi-sensor system with clinical-grade red and infrared light, prioritizing deeper tissue measurement and minimizing artifacts. Garmin HR 3 measures HR with two green LEDs with 32 Hz sampling during standard use and higher rates and 256 Hz during activity tracking.

As for task suitability, these devices are wearable and minimally intrusive, ideal for extended observation in physically demanding work environments.

As for data accessibility and versatility, each device supports cloud or app-based synchronization, enabling the collection of large datasets for subsequent analysis.

Measured data from all three devices are time-coded globally for synchronization and possible further processing. Biostrap and Whoop applications allow data export via APIs and provide SDKs for future user application development.

The individual work processing phases mentioned in our study are Preparation, Cutting, Chopping, Manual Handling, and Other activities. The specifications of the activities are Preparation—preparation of the working tools and machines, moving of the work stuff, preparation of the workplace; Cutting—cutting activities; Chopping—chopping of the wooden part to cut the part of the wood or managing the safety of the cutting; Manual Handling—manual handling of the wooden part to support tree-cutting activities or maintain the safety of the space; Other activities—other non-specified activities related to the working activities such as dressing/ undressing, safety activities, safety device checks, etc.

Based on international recommendations for ergonomic and non-ergonomic working positions [26,36], we used the following definition for the non-ergonomic position:

For the trunk position, the forward tilt was greater than 60 degrees, the tilt was un-supported, and the tilt or rotation of the trunk was greater than 20 degrees; for the head and neck, the forward tilt of the head was greater than 25 degrees; the head tilt, tilt, and rotation were greater than 15 degrees; for the lower limbs, hips, knees, or ankles were in extreme positions (e.g., kneeling); and for the hands; it was the rotation of the forearm. All other working positions were, for use in this case study, considered ergonomically accepted.

This evaluation aimed to monitor the most critical working positions, workload, and critical points for increased workload that is caused by working positions. We did not focuse on the ergonomic evaluation of the working position but on the load parameters.

2.5. Experimental Data Collection

We collected the data on 27 August 2022 in the South Moravia location, tree area Věteřov, Czech Republic. The respondent signed an informed consent. The respondent's ability to perform the required work activity was verified. Before starting the entire study, he was asked to fill out a questionnaire with the data needed for this study. Based on this data, the technical side of the measurement was prepared, including the setting of the participant's parameters.

The experiment took place outdoors, 264 m above sea level, and was performed in the average meteorological conditions of 22.8 °C/53% humidity, wind 4 km/h, and light values 730 lx.

To carry out the measurements and evaluate the results, it was necessary to enter data into the wearable measuring devices that can affect the measurement results, such as the age, height, and gender of the person being monitored. Several wearable sensors were used for the measurements themselves—the Whoop device (Whoop—41.11.4.0. v 17.2.1.0) (fitness and health wearable monitor WHOOP, Boston, MA, USA) and the Biostrap device (Biostrap EVO Recovery set—fitness and health wearable monitor, Biostrap, Duarte, CA, USA, LLC) (Biostrap—EVO—51C6A85F—V1.1.33). A Garmin Fenix 3 HR device (Software: 5.60) (Garmin company, Olathe, KS, USA) was also used. Individual sensors were located on both wrists with rubber wrist bands and on the forearm. Whoop and Biostrap were located on the left hand, Biostrap on the left forearm, and Garmin on the right hand. These wearable sensors were used to monitor workload and to eliminate data distortion and possible loss of data. It also increases the accuracy of data, as Biostrap monitored the rest mode before the workload. We also wanted to be sure that there would be no loss and distortion of data that could arise from the placement of the sensor, movement, sweating, or changes in measurement [39–41].

The Whoop wearable device allows you to measure sleep duration, sleep stages, strain, recovery, heart rate, resting heart rate, heart rate variability, respiratory rate, workouts, and calories burned. The Biostrap wearable device provides the following information using a three-axis accelerometer and a three-axis gyroscope: the measurement of sleep phase, resting heart rate, heart rate variability, blood oxygen saturation, respiratory rate, arterial elasticity, and peripheral elasticity. The Garmin Fenix 3 HR wearable device allows you to monitor heart rate, running dynamics, step length, vertical ratio, and VO2 max, as well as a three-axis compass, altimeter, and barometer options.

As part of this study, the subject was monitored 5 days before the start of the actual experiment and also 5 days after its end to determine the resting value of the heart rate and determine the usual behavior and performance behavior during the performance of work activities and regeneration for the work activities performed. Long-term behavioral measures were not evaluated and were not included in the study itself.

In this case study, physiological parameters were monitored following the required work activity, both during the actual work activity and during breaks and the preparation for the work activity. The course of the actual measurement and the individual measured values were checked and monitored remotely during the measurement using applications for the individual monitoring devices used. A working and video recording of the performed activities was kept.

To compare the load, the use of two different types of saws and two different types of cutting sets was chosen. Measurements were carried out during the processing of already felled Populus Alba white poplars. Cross-sections were performed in both vertical and horizontal orientations. Populus Alba is one of several species of poplar whose original area of distribution includes most of central, eastern, and southern Europe. In the Czech Republic, it is native to the Moravian valleys, and it is the predominant type of poplar in floodplain forests. For the measurements, trunks with a thickness in the section, mainly from 40 to 100 cm, were used. The incisions were made in both horizontal and vertical planes. They were carried out horizontally when cutting off the remaining parts—tree stumps. The wood fibers were, therefore, always cut perpendicularly—these were transverse cuts.

Cutting set A was designed with an STIHL guide bar with a cutting length of 90 cm fitted with a chain with a pitch of 3/8 inch. The thickness of the guide link was 1.6 mm, and the length of the chain was 114 guide links. The cutting links were chisel-shaped. Cutting set B was designed with an STIHL guide bar with a cutting length of 50 cm fitted with a chain with a pitch of 3/8 inch. The thickness of the guide link was 1.6 mm, and the length of the chain was 72 guide links. The cutting links were chisel-shaped.

For chainsaw C, a STIHL MS 500i chainsaw was used. This is a saw that is equipped with direct fuel injection, so it is a saw with a very favorable power-to-weight ratio. The displacement of the saw is 79.2 cc, and the weight of the saw without operating cartridges and cutting set is 6.2 kg. The power of the chainsaw is 5 kW. For chainsaw D, a STIHL MS 362 C-M saw was used. It is a saw of classic construction with an electronically controlled carburetor, so it is a saw with a very favorable power-to-weight ratio. The displacement of the saw is 59 cc, and the weight of the saw without operating cartridges and cutting set is 5.6 kg. The power of the chainsaw is 3.5 kW. This is a classic universal saw used in the Czech Republic.

Configuration for measurement:

AC—For the first set of measurements, the configuration of the cutting set A was selected, which was mounted on chainsaw C. The total weight of the set, including the operating charges, was 10.398 kg. The weight of the set per unit of power thus reached 2.08 kg/kW. This kit was able to make almost all cuts in one cut. This was due to the 90 cm active length of the guide bar. See Figure 1.

BC—The second set of measurements was realized by the configuration of cutting set B mounted on chainsaw C. The total weight of the set, including the operating charges, was 8.791 kg. The weight of the set per power unit, therefore, reached 1.76 kg/kW. The disadvantage was that when cutting thicker trunks than the effective length of the bar (50 cm), these cuts had to be made twice.

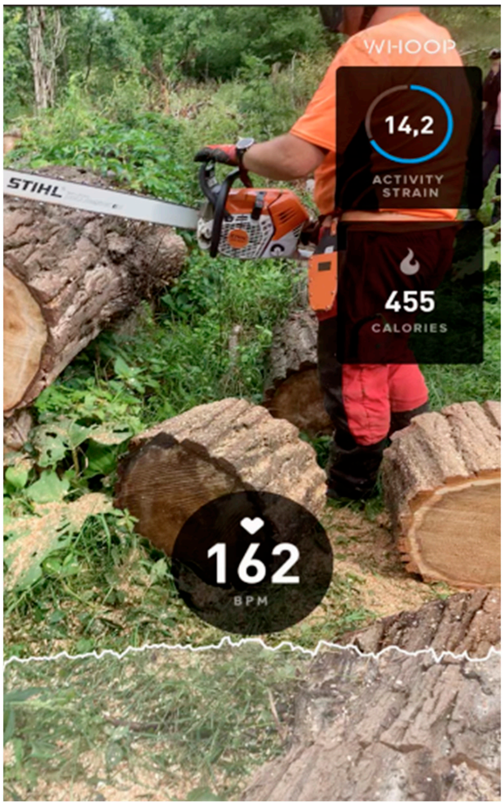

Figure 1. Whoop wearable device software.

BD—The third set of measurements was the configuration of the cutting set C that was mounted on chainsaw D. The total weight of the set was 7.961 kg, including the operating charges. The weight of the set per unit of power was 2.27 kg/kW. So, it was the worst configuration in terms of power to weight. Thus, the saw's lower performance, despite its lower weight, resulted in longer cut times compared with other configurations.

The purpose of this study was to describe the practical application of the simplified index methodology for workload assessment, to show how the methodology works, and how it can be used in everyday practice.

3. Results

3.1. Heart Rate Index Evaluation

Individually measured values were compared to each other with the performed activity and its progress. By comparing the individually measured data, it was found that the difference between the measured values for the individual devices was in the range of 1–15%, which does not affect the overall result. These changes in values could be caused both by the inaccuracy of the measuring devices themselves and, above all, by their placement on the body of the monitored persons.

For the overall assessment of the workload during the performance of individual work activities, based on Formula (1), the time spent by the respondent in a specific area of the workload index range was evaluated according to Table 1.

Based on the comparison of the individual measured data of the duration of the physical load and its level expressed by heart activity during the performance of a specific work activity with the parameters of the permanently permissible load time during the performance of work tasks, an evaluation and analysis of the individual measured values was carried out.

Table 1. Permanent permissible workload by Heart Rate Index.

HR Load	IHR	Permanent Permissible Workload Time Without Rest
105	1.5	3 h
140	2	10–20 min
175	2.5	2–5 min
210	3	1–2 min based on the age

HR Load: heart rate load, IHR—Index Heart Rate. Source [36].

Ensuring the comparability of the heart rate (HR) performance index across studies is critical for understanding physiological responses to workload. Variability in measurement tools, environmental conditions, and analytical methods can complicate comparisons, necessitating a focus on standardization and transparency. Our simplified heart rate (HR) performance evaluation index was originally built on the previous studies [10,42–45] related to the energy expenditure determination linked to HR and VO2 relations.

The main phases of wood processing included Preparation, Cutting, Chopping, and Manual Handling. Other activities included, for example, changing the workplace place or a saw preparation. The section for breaks provides cumulative values for all breaks during work.

Based on Figure 2, we can see that all the devices were used during this case study in all phases of wood processing, which corresponds to the everyday common practice. The biggest time slot is logically covered by cutting, followed by manual handling in case of AC or breaks in other cases. Ergonomic evaluation is mostly related to the time of cutting, which was, for the combination AC, 24:02 min; for BD, it was 22:21 min; and for BC, it was 11:48 min. It can be concluded that for a combination of AC and BD, the time indicates a high workload.

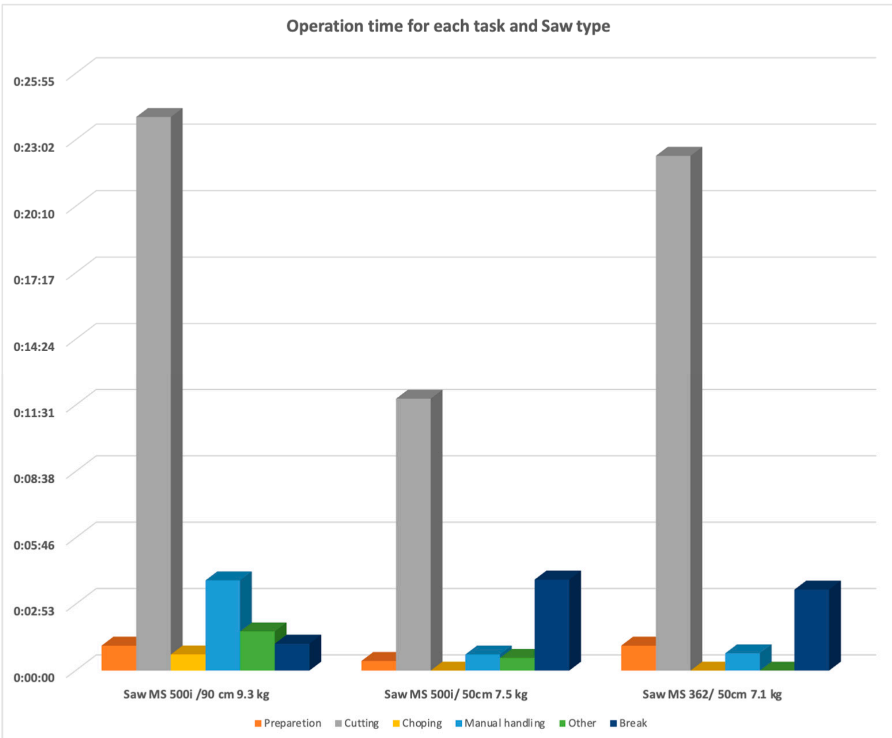

Figure 2. Operation time for each task and saw type.

Wearable devices used to measure HR often vary in their sensor technologies and algorithms, which can produce inconsistent data. It is also necessary to accurately manage the accurate sensor placement and avoid bad measurement habits. Figure 3 shows the average value of heart rate for all three devices—Garmin, Biostrap, and Whoop—during the working cycle. The peak represents the highest value of any of them. We can see that the results of all three devices used are very similar. Although the devices are different, they recorded very similar values of heart rate which can be used for further analysis. There might be minor inaccuracies in values, but it will not influence the final results. Figure 3 contains two curves. One curve is calculated on overall HR minimal measured values from all three sensors—Garmin, Biostrap, and Whoop—and the second curve is calculated as an average of the overall HR maximal values. The differences between values are measurement artifacts and sensor placement differences.

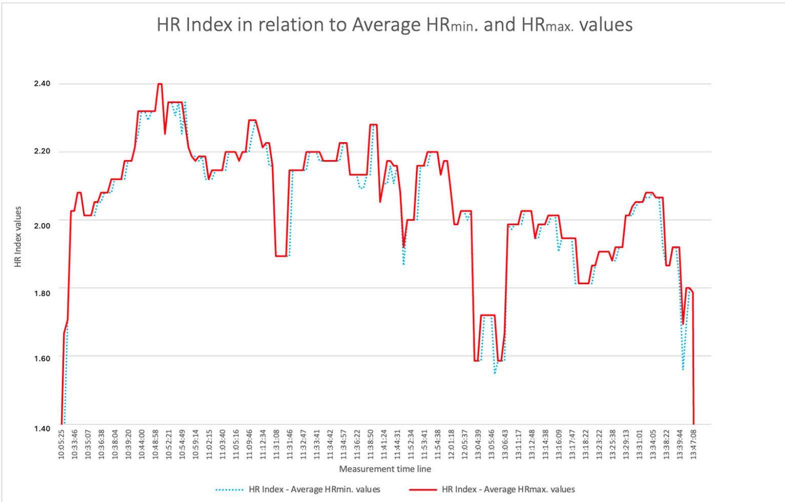

Figure 3. Heart rate during the working cycle.

To assess the possible impact of hand movement and load artifacts and the possible influence of vibrations on the placement of the sensors, we performed a comparison of different placements of the sensors on the arm, forearm, and wrist. Figures 4 and 5 show the differences in the heart rate recording between the arm and the wrist (Figure 4), as well as the differences in the overall assessment of the HR index (Figure 5). The results show that the measurement of the wrist depends on the level of the workload and force used to handle the working tools, such as a chainsaw.

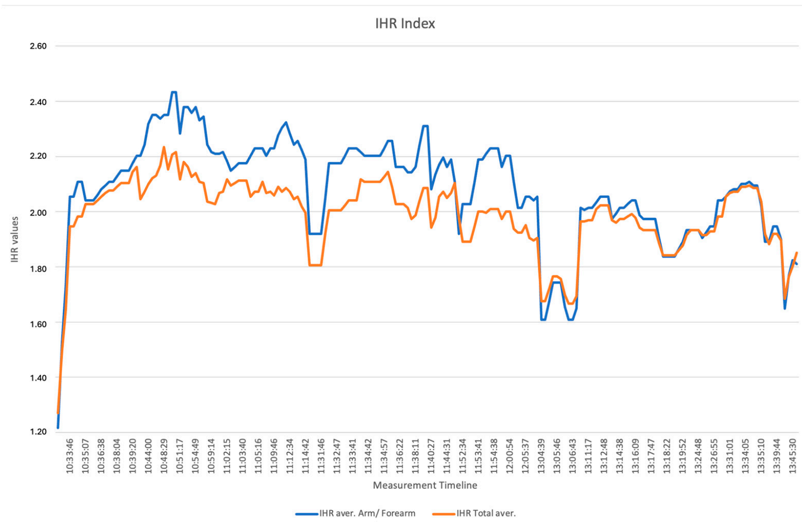

Figure 4. Heart rate measurement based on sensor placement.

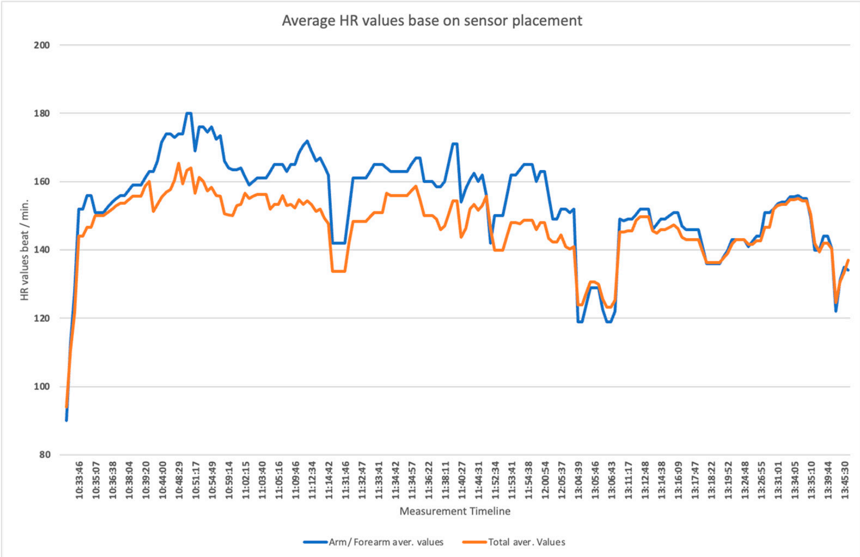

Figure 5. Heart Rate Index in relation to sensor placement.

Figure 6 monitors the heart rate values and a saw type. It is evident that a heavy working instrument, here a saw type MS 500i/90 cm 9.3 kg, can influence the workload, which is much higher than in the two other cases of lighter saws. The physical workload of a worker can be influenced not only by the character of the work but also by the weight of the working tool, which can add to the burden.

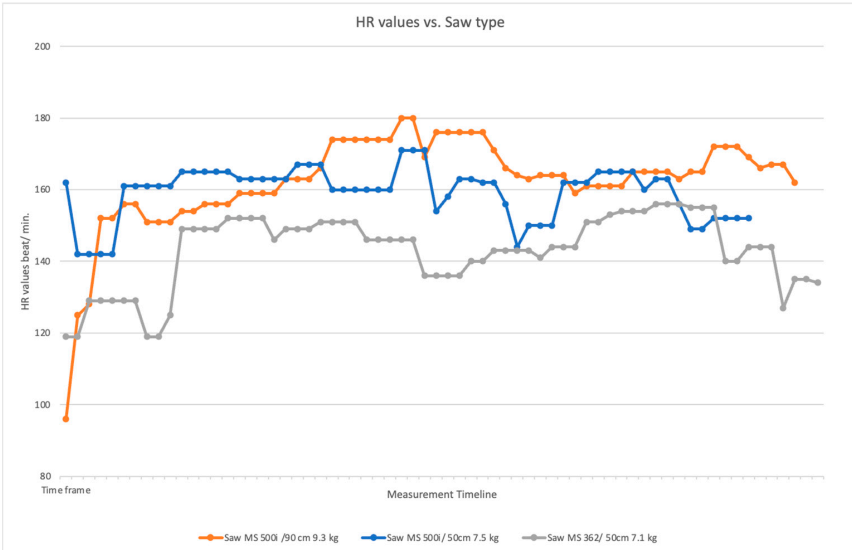

Figure 6. Heart rate values and saw type.

Figure 7 shows, on the axis Y, the value of the Heart Rate Workload Index in combination with different devices for motor-manual tree processing. When we compare type MS 500i/90 cm 9.3 kg and type MS 500i/50cm 7.5 kg, the value of the Heart Rate Workload Index is bigger than workload level 2. In this case, the work should be conducted between 10 and 20 min. In the case of the type MS 500i/90 cm 9.3 kg, almost all working time on level 2 exceeds 20 min, as shown in Table 2. This means that workers should be aware of the time of working operations. The more time they work and exceed the recommended times given by the Heart Rate Workload Index, the more tired they can become, which might lead to mistakes or even accidents. It is important to monitor how long we work and what our tools are, specifically how heavy the tool is.

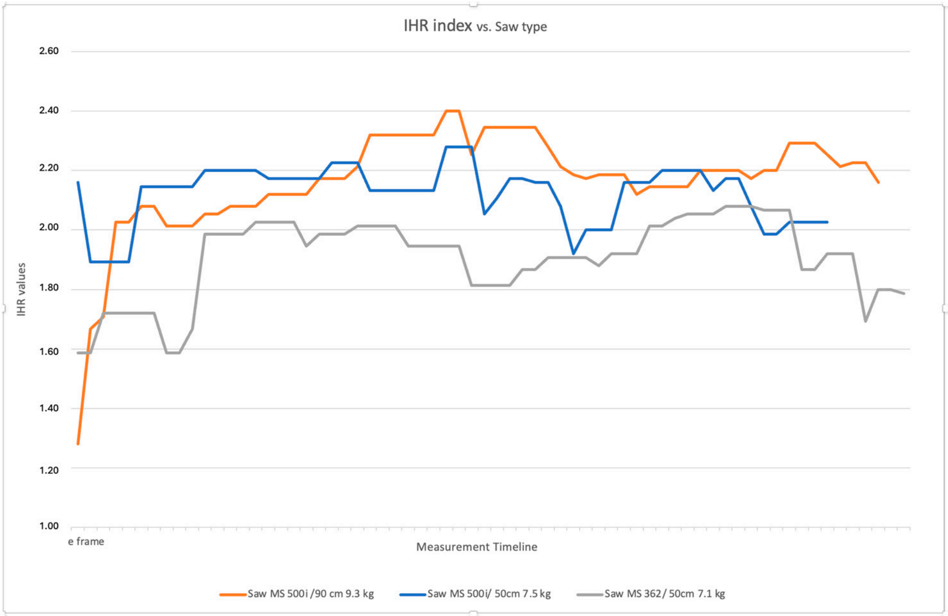

Figure 7. Heart Rate Workload Index and a saw type.

Table 2. Time working cycle and combinations of saws.

Saw Type	Type	Preparation	Cutting	Chopping	Manual Handling	Other	Break	Task Preparation Time	Total Time
MS 500i/90 cm 9.3 kg	AC	0:01:05	0:24:02	0:00:42	0:03:55	0:01:42	0:01:10	0:07:34	0:40:10
MS 500i/50 cm 7.5 kg	BC	0:00:25	0:11:48	0:00:00	0:00:42	0:00:33	0:03:57	0:31:02	0:48:27
MS 362/50 cm 7.1 kg	BD	0:01:05	0:22:21	0:00:00	0:00:45	0:00:00	0:03:31	1:15:21	1:43:03
Total time		0:02:35	0:58:11	0:00:42	0:05:22	0:02:15	0:08:38	1:53:57	

3.2. Influence of Working Positions on Work Performance

Figure 8 presents ergonomic and non-ergonomic working positions in motor-manual tree processing. It contains a line and working phases of cutting, chopping, and manual handling, which are the main parts of motor-manual tree processing and can cause an overload of the musculoskeletal system.

It is evident that the weight of the load affects whether the working position is ergonomic or not and whether we exceed the set parameters. It turned out that when working with the heaviest tool (AC—MS 500i/90 cm 9.3 kg), the worker's body is burdened in non-ergonomic positions for the longest time.

The presented results document that working with a chainsaw includes ergonomic and non-ergonomic activities. The worker should know which are ergonomic positions (as explained in Section 2.4) and the critical load level concerning non-ergonomic positions. From the point of view of health and safety at work, it is important to plan an appropriate distribution of work and rest periods between individual tasks. To work with motor-manual tree processing tools, it would be appropriate to develop a recommendation that takes into account both the working position and the physical load during the work activity, as well as the load caused by the work tool itself.

The results of this study highlight important implications for worker fatigue and productivity, particularly through the lens of time distributions observed in physiological responses. The heart rate (HR) data reveal how different tasks and tools, for example, the use of the different saw types, influence fatigue accumulation, providing actionable insights for optimizing forestry workflows and ensuring worker safety.

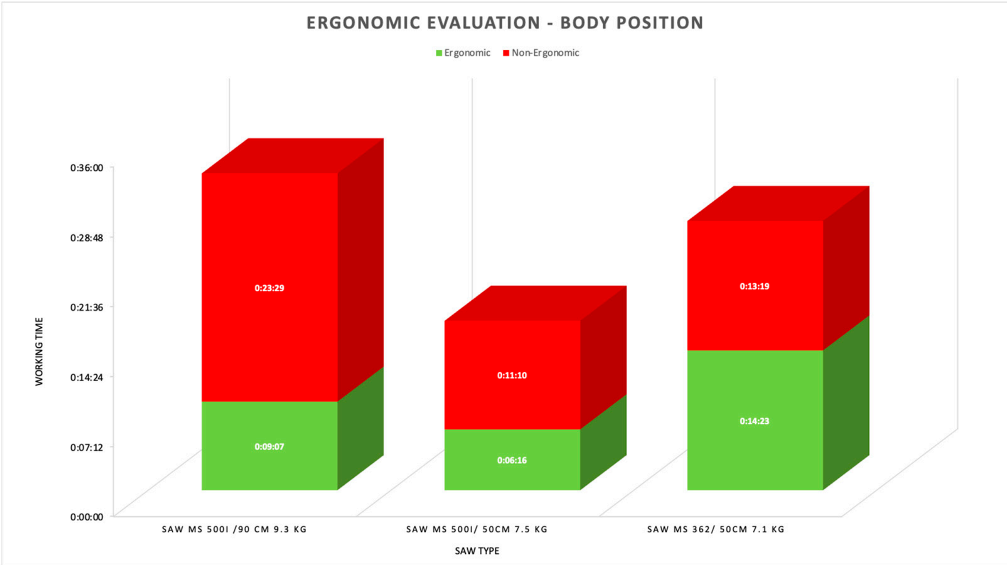

Figure 8. Ergonomic and non-ergonomic working positions in motor-manual tree processing.

Time distributions of HR data showed prolonged periods of elevated cardiovascular strain during tasks involving heavy equipment operation, such as chainsaw use and tree felling. These periods correspond to peak physical effort, which, if sustained without adequate recovery, can lead to cumulative fatigue. Fatigue not only impairs productivity but also increases the risk of errors and injuries, particularly in hazardous environments like forestry. Tasks requiring precision, such as trimming or sorting logs, showed lower HR variability, suggesting a lower physical demand but potentially greater mental fatigue due to the need for sustained focus.

The implications for productivity are twofold. First, the data underscore the need for strategic task rotation to balance physical and mental demands throughout a work shift. For example, alternating between high-intensity tasks, like tree felling, and lower-intensity tasks, such as log sorting, could help reduce overall fatigue. Second, incorporating regular recovery periods, guided by HR thresholds, can mitigate the risk of overexertion and maintain consistent productivity over time.

As for inter-device reliability, the analysis of HR data from multiple devices revealed some discrepancies in readings, particularly during periods of intense hand motion or extensive force to keep working tools in. hands, which may impact HR measured close to the wrist. For example, optical sensors tended to measure HR differently during tasks involving heavy equipment, likely due to motion artifacts, while the forearm monitor provided more stable readings. These inter-device differences underscore the importance of selecting reliable wearables for forestry applications. While forearm/upper hand monitors demonstrated better accuracy, their comfort and practicality during prolonged tasks warrant further evaluation for the Forestry environment. Future efforts should focus on developing applications and the use of good sensors specifically designed for forestry's unique challenges, including vibration resistance, dust, dirt, and sweat-proofing.

The time distributions of HR data provide critical insights into how tasks and tools contribute to worker fatigue and productivity. Addressing inter-device reliability and statistical differences further enhances the credibility of these findings, laying the groundwork for targeted interventions to improve forestry operations. Strategic task rotation, recovery protocols, and the adoption of reliable wearables and ergonomic tools are recommended to optimize worker health and performance.

4. Discussion

To evaluate the performance of a work activity and the workload, we must consider not only the performance of the work itself but also the surrounding influences of the work environment, including the structure of the surrounding terrain, the work aids, the tools used, and the method and intensity of the activity performed. When performing combined work activities, as in our case, it is, therefore, necessary to consider the weight of the work tool and the method of deriving the force or lever, which is important for the performance of the work as part of the total load.

Forestry work presents significant challenges for collecting reliable physiological data due to the intense physical demands and heavy equipment vibrations. These conditions can introduce motion artifacts and disrupt sensor readings, particularly for fashion wearable devices monitoring metrics like heart rate (HR) and heart rate variability (HRV). Ensuring data quality in such environments requires careful planning and mitigation strategies.

From the ergonomic point of view, the primary goal of the activities carried out was to find the conditions to achieve the optimal well-being of the worker during the performance of work, while increasing efficiency protecting health and preventing risks at work.

Forestry work shares many physiological stressors with other high-demand occupations. For example, studies on firefighters consistently report elevated heart (HR) rates and cardiovascular strain during peak activity periods, similar to the trends observed in forestry workers [42,45–47].

Heavy machinery, such as chainsaws and harvesters, generates vibrations that may distort data collected by wearable sensors during wrist placement. Intense physical activities like lifting, climbing, and cutting further exacerbate this issue by disrupting sensor-skin contact and introducing noise into the signals. To address these challenges, wearable devices were chosen, incorporating accelerometers and gyroscopes to differentiate genuine physiological signals from motion-related interference.

Sensor placement was another key factor. Devices were positioned on areas of the body less affected by movement or vibration, such as the forearm or upper arm for the Biostrap device. The worker was instructed to periodically check and adjust sensors during breaks to ensure consistent contact. Data collection was conducted under controlled environmental conditions where possible, reducing variability caused by heat or moisture.

Quality control processes were critical for ensuring reliable data. Anomalies, such as sudden HR spikes inconsistent with physiological responses, were flagged and removed. Data from periods of excessive vibration or motion, identified via accelerometer inputs, were excluded from the analysis. When feasible, redundant measurements were taken using complementary methods to cross-verify results.

While challenges remain, proactive measures such as good quality sensor selection, strategic placement, and rigorous quality checks minimize data disruptions. Future efforts should focus on developing ruggedized wearables and improved algorithms to further enhance data reliability in demanding forestry environments. This study demonstrates the potential for meaningful physiological insights despite environmental challenges.

The future suggested topics for research could implement another element that might influence the performance of the worker such as parameters related to processed wood, relations between physical workload, working positions and body fatigue, the time needed for regeneration, measurement of muscles, idle mode, nutrition, and others.

Wearable technology for physiological measurement in forestry has significant potential to improve worker safety and health. However, its deployment faces challenges related to the demanding conditions of forestry work. These challenges include environmental factors, data accuracy issues, power limitations, user comfort, and privacy concerns. Forestry environments are harsh, characterized by extreme weather, heavy rainfall, and rugged terrain. These conditions can damage standard wearable devices or affect their functionality. For example, sensors may fail when exposed to dust or dirt, while dense vegetation increases the risk of physical damage. Some of the commercial wearable devices not built to withstand such conditions often fail to deliver reliable performance.

The physical demands of forestry work, such as climbing and heavy lifting, may introduce simple devices and motion artifacts, which distort physiological data like heart rate or oxygen levels. Sweat, dirt, and movement can disrupt sensor contact with the skin, leading to incomplete or inaccurate data. Power supply is another critical challenge, as many devices require frequent charging, which is impractical in remote forestry settings with limited access to electricity.

User comfort is also a significant factor. Forestry workers already wear protective gear, and adding wearable devices can be uncomfortable or interfere with mobility. If workers perceive the devices as intrusive, they may be reluctant to wear them consistently. Additionally, privacy concerns about how sensitive physiological data are stored and used may create resistance to adopting the technology. Workers need assurance that their data are secure and used ethically.

To overcome these limitations, wearable technology for forestry must prioritize designs capable of withstanding extreme environments. Devices should be waterproof, dustproof, and impact-resistant, similar to wearable systems used by firefighters. Firefighter observation systems, such as the Hexoskin product, are designed to endure extreme heat and physical impacts and may also provide a useful model for forestry applications.

Improving data accuracy is another key area for development. Advanced algorithms to filter motion artifacts, similar to those in firefighter systems, can enhance data reliability. Hybrid sensor technologies combining optical and electrical methods could further improve accuracy under variable conditions. Additionally, integrating portable and sustainable power sources, such as solar chargers, can address the challenge of limited battery life in remote workplaces.

User-centered design is essential for ensuring that wearable devices are lightweight, ergonomic, and compatible with protective clothing. Smart textiles, like those used in firefighter compression shirts, could be adapted for forestry workers. These materials ensure comfort while maintaining functionality. Data security must also be a priority, with robust encryption and clear policies on data ownership and usage to gain workers' trust.

Finally, incorporating real-time analytics and predictive systems into wearable devices can provide timely alerts for health risks, such as dehydration or heat stress, enabling preventive action. Collaboration between developers, forestry professionals, and researchers, along with field testing, is crucial for refining these technologies for practical use.

By addressing these challenges, wearable technology can transform forestry by improving safety and promoting sustainable work practices, drawing inspiration from proven solutions in similar high-risk industries and supporting them to maintain ergonomics, energy expenditure, and safety activities, including safety support for relatively alone workers.

The findings of this study provide valuable insights into the physiological demands of forestry work, contributing to the broader discourse on occupational safety and health in physically demanding industries. Situating these results within the context of similar research from other sectors, such as firefighting and construction, highlights both shared challenges and unique considerations.

The use of wearable technology in firefighting has revealed that sustained high-intensity tasks, such as carrying heavy equipment or working in extreme heat, result in HR patterns comparable to those documented in this study. These parallels suggest that forestry workers face similarly high levels of cardiovascular stress, underlining the need for targeted interventions like scheduled rest periods and hydration protocols to mitigate fatigue and heat stress.

In construction, research has shown that prolonged physical exertion combined with environmental challenges like heat and noise leads to similar physiological strain. However, unlike construction workers, forestry professionals often operate in remote environments with limited access to immediate medical assistance or cooling mechanisms. This distinction emphasizes the importance of robust, real-time monitoring systems for forestry to detect early signs of exhaustion or heat-related illness, enabling preemptive measures.

Mining, another physically demanding industry, often involves prolonged exposure to vibration from heavy machinery, which mirrors the challenges in forestry. Studies in mining have demonstrated the detrimental effects of vibration on wearable sensor accuracy and worker health. Similar findings in this study highlight the need for improved wearable technologies capable of withstanding such conditions without compromising data reliability.

Comparisons with these industries reinforce the significance of the findings and their implications for worker safety. The physiological demands observed in forestry align with those in other demanding fields, suggesting that strategies effective in firefighting or construction, such as enhanced training, optimized schedules, and improved ergonomic tools, could benefit forestry workers as well.

Moreover, this study contributes to the growing body of evidence that wearable technology is a viable tool for monitoring occupational health, even in challenging environments. However, the results also underscore the limitations of current devices in handling vibration and motion artifacts, a challenge shared across industries. This highlights an opportunity for interdisciplinary collaboration to develop next-generation wearables designed for high-stress, physically demanding contexts.

By comparing these findings with research from other industries, this study also underscores the universal importance of addressing physiological stress in physically demanding jobs. It also highlights the unique needs of forestry workers, reinforcing the necessity of tailored solutions to enhance safety, health, and performance in this critical sector.

This study highlights the practical application of a simplified index methodology for workload assessment, demonstrating its functionality and utility in everyday practice. It underscores the importance of users carefully considering specific factors when applying this method to achieve optimal results in workload evaluation. The methodology is designed to be versatile and applicable to a wide range of manual, moto-manual, or combined activities in forestry. Chainsaw cutting was intentionally selected as an example due to the potential challenges associated with heart rate measurement, such as the influence of sensor placement and the nature of the activity, making it a particularly relevant scenario for showcasing the method's robustness.

We took into account the following limitations of this study:

- Limited Sample Size: The physiological and ergonomic results may vary widely among different individuals due to variability in physical characteristics, skills, and work habits.
- Focus on Short-Term Observations: Long-term behavioral measures and physiological impacts were not included. This study did not assess the long-term consequences of workload and ergonomic challenges on worker health and safety.
- Potential for Measurement Errors: While multiple wearable devices were used to mitigate data distortion, inaccuracies in measurements (1–15% difference) due to device placement or motion artifacts were noted. This could slightly but not significantly affect the precision of results.
- Environmental and External Factors: We did not take into account separately the impacts of the workload extension increased by multiple environmental and external factors. This study did not separately account for influences such as varying terrain, extreme weather conditions, or other stressors that could impact workload and ergonomic conditions in real-world scenarios.
- Specific Equipment Configurations: The focus was taken only on particular chainsaw models and configurations, which may not reflect the diversity of tools and equipment used in similar forestry operations globally. This limited list of tools was used only as an example of the method application for different conditions.

5. Conclusions

The purpose of this study was to describe the practical application of the simplified index methodology for workload assessment, to show how the methodology works, and how it can be used in everyday practice. In this study, we wanted to point out that users could use this method in practice to obtain the best possible results for their workload assessment. We assume that the methodology can be used for any manual, moto-manual, or combined activity in forestry. We have deliberately chosen chainsaw cutting for this example because it is the activity where the results of heart rate measurements using wearable devices may be most affected by sensor placement or working activities.

Based on the measurements and evaluation of the results, it was proven that the use of a heavier work tool with a long cutting blade, type AC: MS 500i/90 cm 9.3 kg, significantly contributes to the creation of a non-physiological working position and to an increase in the energy required to perform work, which, in our case, was represented by an increase in heart rate. On the other hand, with a lighter work tool with a shorter cutting blade, both a decrease in heart rate and a reduction in the time during which work activities are performed in a non-physiological position were observed when performing a similar work activity.

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