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Physiological responses of operators to handle vibration of diesel-fueled single-axle tractor

Siraj K. Busse[1]*, Anthony N. Sinclair[2], Diresibachew H. Wondimu[3] and Daniel T. Redda[1]

[1]School Mechanical and Industrial Engineering, Addis Ababa Institute of Technology, Addis Ababa University, Addis Ababa, Ethiopia.
[2]Department of Mechanical and Industrial Engineering, University of Toronto, Toronto, Canada.
[3]Department of Physiology, School of Medicine, College of Health Sciences, Addis Ababa University, Addis Ababa, Ethiopia.

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Hand-arm transmitted vibration originating from a 15 horsepower single-axle tractor can be very strong and cause operator fatigue plus various physiological disorders in vascular, neurological, and musculoskeletal systems. The objective of this work was to measure the characteristics of such hand-transmitted vibrations and its effect on the health of the single-axle tractor operator, in a research program conducted at the Melkasa Agricultural Research Center of Ethiopia. During the study, the measurement of anthropometric data and the heart rate of the operators and vibration at the handle of single axle tractor were conducted. From measured data, the requirement of expenditure energy, physical workload, and operators' daily vibration exposure was calculated. The average measured resting heart rate, working heart rate and heart rate after the operation was 71±7, 162±4 and 126±24 beats/min, respectively. The calculated values of HR reserve (%HRR) or physiological workload and the ratio of working to resting heart rate were 74±10% and 2.3±0.4 ($p < 0.0001$), respectively. The total energy expenditure of single-axle tractor operators was calculated to be 35±1.2 kJ/min. The daily exposure m/s^2A (8) and total exposure points which were calculated indirectly from measured vibrations at the tractor handle and duration of operation were 12.6 m/s^2 and 2520 points, respectively. From measurements of operators' heart rates, it was concluded that the physical workload fell into the category of extremely heavy work, for which the working heart rate more than doubled the resting heart rate ($p < 0.0001$).

Key words: Tractor vibration, hand-transmitted vibration, single-axle tractor, heart rate, physical workload, vibration exposure.

INTRODUCTION

Currently, the government of Ethiopia supports both agricultural machinery importers and domestic

*Corresponding author. E-mail: srjkedir@gmail.com.

agricultural machinery manufacturers, to promote food security by increasing agricultural productivity. The percentage of a country's population employed in agriculture has a tendency to decrease with the advancement of national economic development, due to the increase in secondary and tertiary industries. This progression is supported by increased utilization of large-, medium- and small-scale farm machinery that promotes increased agricultural productivity (Sakai, 1990). Therefore, single-axle tractors are very important for small-scale farmers in the drive to shift from animal-powered farming to engine-powered farming systems. Single-axle tractors are multipurpose machines designed primarily for rotary tilling and other farm operations. A single-axle tractor is also known as a hand-tractor, walking-tractor, walk-behind tractor, etc., (Sakai, 1999). When a tillage implement is attached to a single axle tractor, the system is called a power-tiller. Mechanical vibration arises from a wide variety of processes and operations performed in industry, mining, construction, forestry, agriculture, and public utilities. Whole-body vibration occurs when the human body is supported on a surface which is vibrating, e.g. in most forms of transport and in close proximity to some types of industrial machinery. Hand-transmitted vibration occurs when the vibration enters the body through the hands, typically in various work processes where rotating or percussive power tools or vibrating workpieces are held by the hands. The human response to vibration depends mainly on the magnitude, frequency, and direction of the vibration signal (Griffin, 1990).

Mechanical vibration is the oscillatory motion of an elastic solid (or liquid) body about a reference position. All bodies with mass elements and elasticity are capable of vibration; hence, most machines and structures including the human body can experience vibration. According to Griffin (1990), human response vibration depends mainly on the magnitude, frequency, and direction of the excitation source. In the ISO Standard (ISO-5349, 2001) for measurement and evaluation of human exposure to hand-transmitted vibration, the most important quantity used to describe the magnitude of the vibration transmitted to the operator's hands is the root-mean-square (RMS) frequency-weighted acceleration expressed in m/s^2. The RMS magnitude is correlated with the vibration energy, and hence the vibration injury potential or destructive capability over a period of time. The hand-transmitted vibration of a single-axle tractor is very strong because the handle grip is a cantilever beam, with the excitation power obtained from the one-cylinder diesel engine (Ying et al., 1998). The low-frequency vibrations to which the operator is subjected result from both linear displacements of the single-axle tractor and rotational oscillations of the pitch and roll modes (Mehta et al., 1997). The four principal effects of ride vibrations are considered to be degraded health, impaired activities, impaired comfort and motion sickness. Daily exposure to hand-arm vibrations over a number of years can cause permanent physical damage known as 'white finger syndrome' or can damage the joints and muscles of the wrist and the elbow. White finger syndrome in its advanced stages is characterized by blanching of the extremities of the fingers, which is caused by damage to the arteries and nerves in the soft tissues of the hand (Shen and Ronald, 2017). Griffin et al. (2003) measured hand-transmitted vibration on representative samples of the vibratory tools used by the subjects in several study populations. Raw vibration magnitudes were expressed as root-mean-square acceleration values over the frequency range of 6.3 to 1250 Hz. Amplitude data were also presented using the W_h frequency weighting system that places a larger weight on frequencies that pose a higher biological risk (ISO-5349, 2001). For each tool used in the study, vibration measurements were made at each hand position in three orthogonal directions: x, y, and z as shown in Figure 1. In each case, the greatest of the three magnitudes was selected to represent the vibration magnitude of the tool. According to ISO 5349 (2001) for most power tools, the vibration entering the hand contains contributions from all three orthogonal axes of motion.

The frequency-weighted RMS acceleration values for the x-, y- and z-axes, a_{hwx}, a_{hwy}, and a_{hwz} respectively, are reported separately using the frequency weighting graph. The one-third-octave band frequencies from 6.3 to 1250 Hz constitute the primary frequency range and the calculated a_{hw} includes all one-third-octave bands within this range, where:

$$a_{hv} = \sqrt{a_{hwx}^2 + a_{hwy}^2 + a_{hwz}^2} \quad (1)$$

Frequencies outside the primary range do not generally make an important contribution to the value of a_{hw} and may be excluded from the calculation (ISO-5349, 2001). The evaluation of daily vibration exposure is based on the vibration magnitude a_{hv} and the daily exposure duration. In order to facilitate comparisons between daily exposures of different durations, the daily vibration exposures are expressed in term of 8-h energy-equivalent frequency-weighted vibration total value, $a_{hv(eq,8h)}$, as shown in Equation 2. For convenience $a_{hv(eq,8h)}$ is given the shorthand notation of A(8) (ISO-5349, 2001):

$$A(8) = a_{hv}\sqrt{\frac{T}{T_0}} \quad (2)$$

where T = the total daily duration of exposure to the

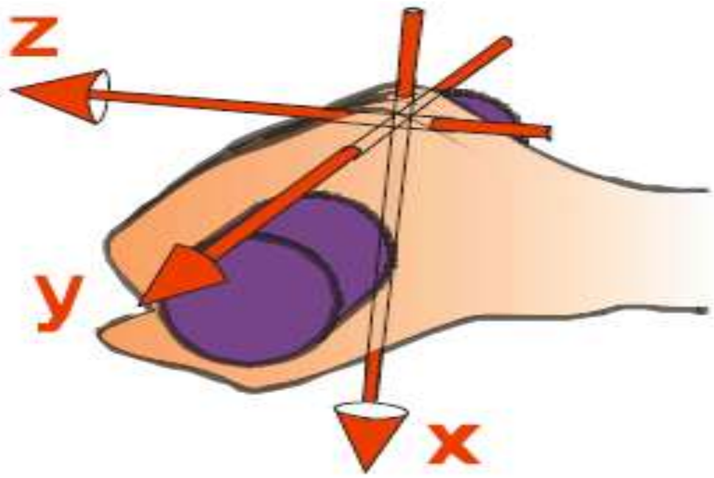

Figure 1. Three orthogonal directions of vibrational motion (ISO-5349, 2001).

vibration, called "trigger time"; T_0 = the reference duration of duration 8 h.

Studies by Muhammed et al (2003) have shown that the heart is a great information processor. Resting heart rate is measured under the condition of no physical exertion. It is best measured in the morning before any stress, caffeine or much movement. Maximum heart rate (HR_{max}), on the other hand, is an estimate of heart rate that someone could (not should) achieve during maximum physical exertion. A rough estimate of a person's HR_{max} can be obtained by subtracting the person's age from 220 (Vonda and Ruth, 2009).

$$HR_{\max} = 220 - age \text{ (in years)} \quad (3)$$

Several studies have been conducted to determine the physical workload on an operator imposed by various machines (Muzammil et al., 2004; Çalıskan and Çaglar, 2010; Eroglu et al., 2015). Sarzynski et al. (2013) suggested that the maximum workload is roughly indicated by achieving 85% of age-predicted maximum heart. Percentage Relative Heart Rate (%HRR) can be determined by applying the formula (Çalıskan and Çaglar, 2010; Vitalis, 1987):

$$\%HRR = \frac{HR_w - HR_r}{HR_{\max} - HR_r} * 100 \quad (4)$$

where HR_w = average working heart rate, bpm; HR_r = resting heart rate, bpm; HR_{max} = maximum heart rate, bpm.

According to several studies (Çalıskan and Çaglar, 2010; Eroglu et al., 2015; Lammert, 1972), the half of heart rate reserve (50% level) of the working heart rate was determined by using the formula:

$$50\% level = HR_r + \frac{HR_{\max} - HR_r}{2} \quad (5)$$

Last, the ratio of working heart rate (HRw) to resting heart rate (HRr) is obtained from (Çalıskan and Çaglar, 2010; Eroglu et al., 2015):

$$Ratio = \frac{HR_w}{HR_r} \quad (6)$$

Basal metabolic rate (BMR) is the minimal rate of energy expenditure compatible with life. It is measured in the supine position under standard conditions of rest, fasting, immobility, thermoneutrality and mental relaxation. Depending on its use, the rate is usually expressed per min/h or per 24 h (FAO et al., 2001). Several studies have been conducted by different researchers on regarding the amount of energy required by an operator using various types of machines (Pawar and Pathak, 1980; Tiwari and Gite, 2002; Katherivel et al., 1991), the BMR was then evaluated by several researchers for assorted population samples and activities (Kroemer and Grandjean, 2000). Borah (2015) has evaluated the physiological workload of hill farm women of Meghalaya and determined heart and energy expenditure. Çalıskan and Çaglar (2010) have classified the grade of physical work as resting, very light work, moderate work, heavy work, very heavy work and extremely heavy work based on the data of energy expenditure, heart rate, and physical workload. Food and Agriculture Organization of the United Nations (FAO), World Health Organization (WHO) and United Nations University (UNU) (FAO/WHO/UNU) expert consultation (WHO, 1985) estimated the requirement of energy expended by adults as multiples of BMR (WHO, 1985). This was later called “physical activity level” (PAL) in a manual commissioned by FAO for the calculation of human energy expenditure (FAO, 2001). PAL is defined as the total energy required over 24 h divided by the basal metabolic rate over 24 h (James and Schofeild, 1990). Schofield estimated the basal metabolic rate as 0.063 W + 2.896 in +/- 0.641 MJ/day or 15.057 W + 692.2 +/- 153 kcal/day, where W is the weight (kg) of adults in the age range of 18 to 30 years old (FAO, 2001; Schofeild, 1985). Total energy expenditure is given by BMR × PAL, where the value of PAL for different physical activities is given in the report of FAO (2001).

The hand-arm vibration exposure calculator enables a quick determination of the number of exposure points for every hour of exposure time for any given individual process; this then yields the time to reach the vibration Exposure Action Value (EAV) (equal to 2.5 m/s^2 of A (8) or 100 points) and time to research the vibration Exposure Limit Value (ELV) of 5 m/s^2 of A (8) or 400 points. The calculator also calculates the Partial Exposure, which is the vibration exposure (shown in both A (8) in m/s^2 and exposure points) for the process and is calculated from the vibration magnitude and the exposure duration. The daily exposure of A (8) in m/s^2 and total exposure points can be calculated by summing the Partial Exposures (HSE, 2005). This document also offers suggestions with respect to reducing risks posed by high vibration amplitudes.

A word of explanation on notation: The action value was set at a vibration magnitude of 2.5 m/s^2 and the limit value to 5 m/s^2. Both of these figures are A(8) values, meaning they are average vibration magnitudes over the course of an 8-h workday. According to the European Commission Directives (2002) when the EAV is reached, a program of measures to eliminate or reduce exposures to hand-arm vibration must be implemented. When the ELV is reached, immediate action to prevent exposure above the limit value must be taken, and the reasons for exceeding the ELV must be identified (Commision, 2002). According to the European Directive 2002/44/EC (Commision, 2002) on the minimum health and safety requirements regarding the exposure of workers to vibration, hand-arm vibration exposure management can be simplified by using an exposure “points” system. Exposure points are simply added together, so the maximum number of exposure points can be set for a person in one day. The exposure scores corresponding to the exposure action and limit values are (Commision, 2002) exposure action value (2.5 [m/s^2]) = 100 points (maximum points for exposure action value (EAV)) and exposure limit value (5 [m/s^2]) = 400 points (maximum points for exposure limit value (ELV)).

Dong (1996), in his study on vibration transmitted by the handles of a GN-5 type model walking tractor, concluded that the main cause of vibration was the engine. Also, he found that the vibration on the handles of the GN-5 walking tractor was very strong and seriously affected the operator’s health. Mehta et al. (1997) measured ride vibrations on a single axle tractor with a seating attachment under various operating conditions and compared them with the values specified under ISO-2631 (1985) in relation to working efficiency, health, and safety of the operator. They found that exposure time for the single axle tractor should not exceed 2 to 5 h per day for rototilling operations. Mamansari (1998) reported that the vibration level of a single-axle tractor increased with an increase in engine speed in both the stationary and transport modes; the vertical vibration component varied significantly in various parts of the tractor handle and was highest at the handle tip. Ying et al. (1998) reported that the major source of vibration excitation of Hand-Transmitted Vibration (HTV) of a walking tractor is the engine, and found that the highest amplitude of vibration was in the x (vertical) direction. The main objective of this paper was to measure and analyze the hand-transmitted vibration characteristics of a 15 horsepower single-axle tractor, in terms of amplitude, the orientation of motion, and safety level according to international standards.

MATERIALS AND METHODS

Experimental layout

The evaluation of vibration characteristics of hand-arm transmitted vibration originating from a single-axle tractor was conducted at the Melkasa Agricultural Research Center (MARC), located at 117 km East of Addis Ababa. The region features arid to semi-arid agro-ecological zones, at an altitude of approximately 1550 m above sea level with temperatures generally ranging from 14 to 28°C, average annual rainfall of 750 to 800 mm, Length of Growing Period (LGP) of 3 to 6 months, and sandy soil of volcanic origin with pH ranging from 7 to 8.2.

Equipment

A single-axle 15HP Dong Feng tractor with the implement, model 2b-DF-15L with a horizontal 4-stroke diesel engine with a crankshaft turning speed of 2000 rpm was used for all data collection. A model VM-6380 vibration meter Tester (M&A Instruments, Arcadia, CA) with a 3-axis piezoelectric accelerometer vibration sensor (Figure 2) was used for vibration measurements. The sensor bandwidth of 10Hz to 10 kHz includes the relevant frequency range of 6.3 to 1250 Hz for this type of assessment (ISO-5349, 2001).

The heart rate of each tractor operator was measured by a Polar T31 Coded Heart Rate Transmitter and Belt Set, using high precision bluetooth heart rate sensors connected to a Polar A370 fitness tracker manufactured by the Polar Global Company (Figure 3). The Polar heart rate receiver component (receiver wirelessly)

a b

Figure 2. (a) VM-6380 3-Axis 3D Digital Vibration Meter Tester. (b) Field measurement of vibration characteristics.

Figure 3. Polar T31 Coded Heart Rate Transmitter and Belt Set with Polar A370

Figure 4. Finger Pulse Oximeter with digital blood pressure monitor (Contec Medical Systems Co., Ltd. China).

receives the heart rate signal from the T31 Polar coded transmitter belt, which is slim, light and waterproof. The transmitter, worn around the chest of operators transmits a pulse corresponding to each heartbeat.

A Contec CMS-08A digital blood pressure monitor with finger pulse Oximeter shown in Figure 4 was used to measure blood pressure and oxygen saturation of the single-axle tractor operators.

Study subjects and tasks

Melkasa Agricultural Research Center is the federal research center which is working on agricultural mechanization research to improve the living standard the farmers. For its material and research facilities this place was selected for this research work. All the operators were from this research center and they have been trained how to operate the single axle tractor and they have operated several times before the test was conducted.

The mean and standard deviation of anthropometric data of age, height, weight, and body mass index (BMI) of the seven operators of the single-axle tractor was found to be 26 ± 3 years, 170 ± 8 cm, 55 ± 4 kg and 19 ± 1 kg/m^2, respectively.

Seven male subjects participated as operators of the 15-HP single-axle tractor. The operators performed tilling tasks on previously tilled land with the tractor in third gear, while the vibration levels were measured at the tractor handle along the x (vertical), y (forward), and z (transverse) axes. Note that the y- and z-directions were switched from those shown in Figure 1 which corresponds to the ISO 5349 (ISO-5349, 2001) because the handle on this particular tractor model operator was oriented at 90 degrees from that shown in Figure 1. The heart rates of the single-axle tractor operators were measured and recorded before the operation, during operation at 5-min intervals for 25 min and 5 min after completion of tractor operation. The blood pressure and oxygen saturation levels of the operators were also measured at those times.

RESULTS AND DISCUSSION

Vibration data

The 3-axis piezoelectric accelerometer vibration sensor was attached at the handle of the single-axle tractor, adjacent to the hand of the operator. An RS-232C data cable link connected the sensor to a laptop computer running the XP Windows operating system, to record the vibration data. The mean and standard deviation of measured vibration values on three axes were 22.7±2.85, 11.4±4.44 and 20.90±2.26 m/s^2 in x, y and z directions, respectively. The calculated vibration total value a_{hv} and vibration daily exposure A (8) in m/s^2 (calculated using Equation 2) at the handle of the single axle tractor averaged 32.9 and 12.6 m/s^2, respectively.

Evaluation of vibration exposure

From calculated values of a_{hv}, the vibration exposure was determined according to the Control of Vibration at Work Regulations that are based on the 2002 EU Physical Agents (Vibration) Directive (Commision, 2002). Vibration total value and daily exposure of A(8) in m/s^2 were calculated using Equations 1 and 2. The vibration daily exposure of A(8) was also calculated from vibration total value and duration of exposure by using the Hand-Arm Vibration Exposure Calculator designed by the Health and Safety Executive (HSE, 2005) shown in Figure 5.

Based on the exposure calculator, the vibrations picked up by the operator's hands will reach the EAV of 2.5 m/s^2 of A (8) after only 3 min and ELV of 5 m/s^2 of A (8) after only 11 min.

The calculated daily exposure of 12.6 m/s^2 of A (8) is well above the Action Limit Value (5 m/s^2); the 2520 Total Exposure points are also well above the limit of 400 points. The data indicate that safe vibration limits are routinely exceeded in a day of normal use of a single-axle tractor, and the operators are at significant risk of developing Hand-Arm Vibration Syndrome (HAVS). Ahmadian et al. (2014) have shown that 10% of all operators of a 13-HP walking tractor with vibration total value range of 14 to 26 m/s^2 will be affected by Hand-Arm Vibration Syndrome within 2.32 years. Similarly, Parvin et al. (2014) determined a total vibration amplitude a_{hv} of 16.95 m/s^2 for roto-tilling and determined the permitted working time for such machinery was only a few seconds. They suggested a risk of musculoskeletal disorders and recommended measures to reduce hand-arm vibration transmitted to the tiller user's hands.

Physiological characteristics of the operators

The mean and standard deviation of measured diastolic blood pressures of the seven tractor operators, before and after operation of the tractor, were 73 ± 7 and 77 ± 9 mm Hg, respectively; the mean and standard deviation of measured systolic blood pressure of the seven tractor operators, before and after tractor operation was 122 ± 12 and 119 ± 7 mm Hg, respectively. The average measured oxygen saturation levels of the seven tractor operators decreased from 98 ± 1 to 96 ± 1%; these levels are within normal range.

The operators' heart rates were measured 5 min before tractor operation, every 5 min during operation for 25 and 5 min after tractor operation. This yielded mean measured heart rates of operators before, during and after operation of 71±7, 162±4 and 126±24 bpm, respectively (Figure 6). The average measured resting heart rate for our 7 tractor operators of 71 ± 9 bpm was within the normal range of normal resting heart rates of 60 to 100 bpm (Seol et al., 2017). Similar measurements by various researchers (Çalıskan and Çaglar , 2010; Eroglu et al., 2015; Kirk and Parker, 1996; Melemez et al., 2011) yielded values from 60 to 79.6 bpm for operators of different machines. An age-dependent predicted maximum heart rate was calculated using Equation 3 and found to be 194 ±2.6 bpm. Various researchers (Eroglu et al., 2015; Cristofolini et al., 1990; Abeli et al., 1994) obtained results for this parameter varying from 127 to 178 bpm for their particular machine

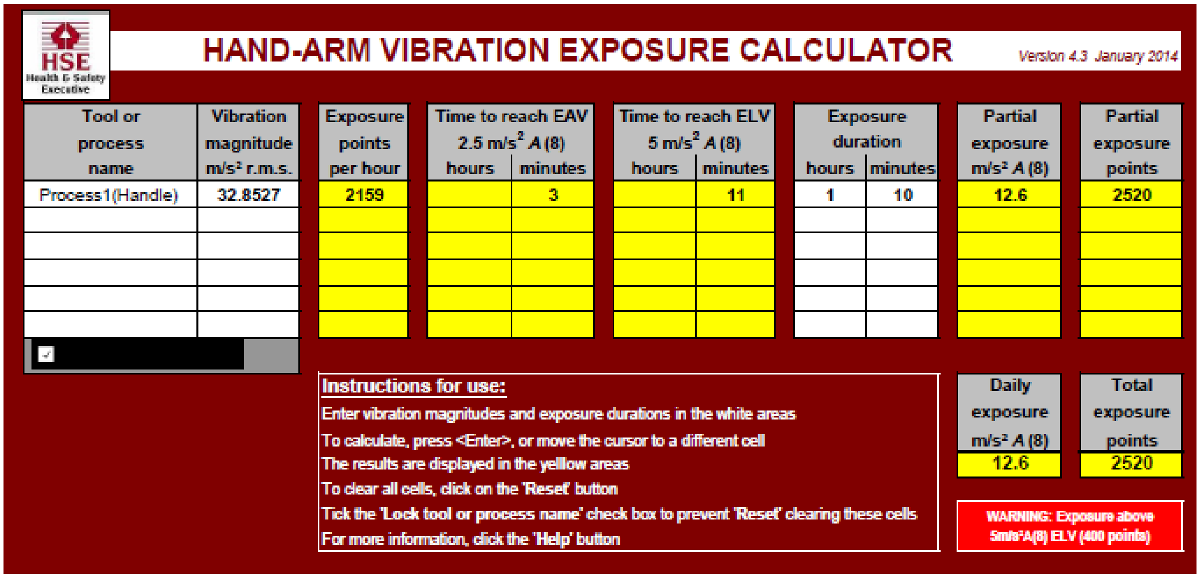

Figure 5. Hand-arm vibration exposure calculator and calculated results (HSE, 2005).

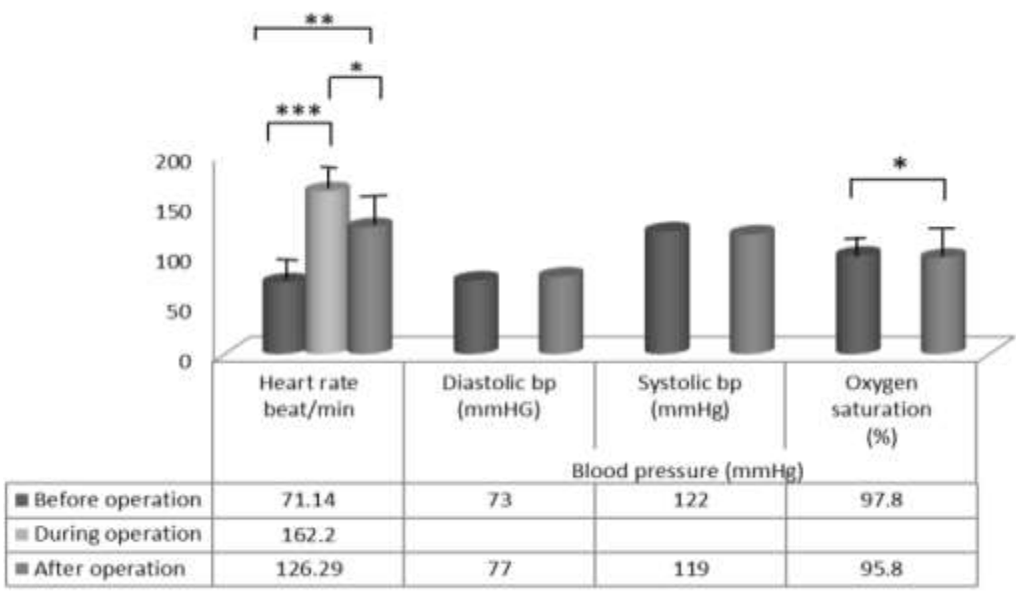

Figure 6. Physiological parameters of single axle tractor operators and their significance. *Significant difference, p < 0.01, **Significant difference, p < 0.001, ***Significant difference, p < 0.0001.

operators. The average measured working heart our seven single-axle tractor operators was 162±4 bpm; this value is very high compared to values of 77 to 120.9 bpm reported by other researchers on a variety of machines (Abeli et al., 1994; Apud and Valdes, 1995; Kirk and Sullmn, 2001; Çalıskan and Çaglar , 2010; Eroglu et al., 2015; Muzammil et al., 2004; Shemwetta et al., 2002; Tiwari and Gite, 2001).

According to Afshari et al. (2017) in the study of the determination of work-rest schedules based on physical workload they have categorized the workload with working heart rate above 160 bpm as “extremely heavy work”.

The average estimated percent heart rate reserve

(%HRR), which is an indication of physiological or level of physical activity of the tractor operators was 74% in the present study. Other researchers (Çalıskan and Çaglar , 2010; Eroglu et al., 2015; Abeli et al., 1994; Kirk and Sullmn, 2001) had significantly lower values in the range of 29 to 64%. The ratio of average measured working heart rate (HRw) to the calculated 50% level of heart rate reserve for the single-axle tractor operators was 1.22 ± 0.11; this value place the work in the category of work "continuous heavy duty" (Eroglu et al., 2015; Lammert, 1972). By comparison, this ratio was found to be only between 0.82 and 0.97 in other studies (Çalıskan and Çaglar , 2010; Eroglu et al., 2015; Lammert, 1972). The ratio of working heart rate to resting heart rate for our seven tractor operators was found to be 2.28±0.39, compared to values of 1.37 to 1.75 in other studies (Çalıskan and Çaglar , 2010; Eroglu et al., 2015; Vitalis, 1987; Afshari et al., 2017). Using the equation for basal metabolic rate (BMR) proposed by Schofield (1985), the calculated BMR was calculated to be 14.6± 0.5 kJ/min or 3.5±0.1 kcal/min.

From these working heart rate results, it was concluded that this work falls into the category of "unduly heavy work" and the physical activity level (PAL) was 2.4 (Afshari et al., 2017). Therefore, from PAL and BMR calculations, the average energy expenditure level of the single-axle tractor operators was found as 35±1 kJ/min or 8.4±0.3 kcal/min. Other studies conducted with a variety of machinery types (Katherivel et al., 1991; Kroemer and Grandjean, 2000; Pawar and Pathak, 1980; Shemwetta et al., 2002; Tiwari and Gite, 2002) yielded results in the range of 7 to 18 kJ/min.

Conclusion

Vibration data were collected at the handle of a 15-HP single-axle tractor while performing routine tilling operations. Various physiological parameters were measured and analyzed. The Daily Exposure in m/s^2 A (8) of vibration at the tractor handle was 12.6 m/s^2 and total exposure points were 2520. In both cases, the A (8) exposure limit value of 5 m/s^2 and total exposure points of 400, was greatly exceeded. From measurements of operators' heart rates, it was concluded that the physical workload fell into the category of extremely heavy work, for which the working heart rate more than doubled the resting heart rate ($p < 0.0001$). This very high physical workload has a strong impact on operators of single-axle tractors over extended periods of time and may lead to the risk of different musculoskeletal disorders.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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