

## **A New Method for the Experimental Assessment of Finger Haemodynamic Effects Induced by a Hydraulic Breaker in Operative Conditions**

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**Abstract:** A New Method for the Experimental Assessment of Finger Haemodynamic Effects Induced by a Hydraulic Breaker in Operative Conditions: Matteo VALENTINO, *et al.* Clinic of Occupational Medicine, University of Ancona, Italy—The haemodynamic effects, in terms of grip force and hand-transmitted accelerations, produced on the fingers of 10 healthy subjects by operation of a hydraulic breaker held with a low or a high grip were investigated with a new experimental set-up. A novel apparatus consisting of a capacitive sensor matrix and a laser Doppler vibrometer was used to measure the two parameters during breaker operation. Finger blood flow in basal conditions and after each test was evaluated in the four long fingers of both hands with a photoplethysmograph and superficial skin thermometry. The amplitude of the accelerations transmitted to the hand surface was greater during the test with the low grip. Photoplethysmographic and thermometric values were significantly lower than basal values after either test. The amplitude of photoplethysmographic values during the tests was significantly lower with the low than with the high grip in 6 subjects, in both index fingers, and in the right middle finger. The authors show that the level of grip force used for holding the breaker causes transmission of vibrations of wider amplitude, resulting in greater reduction in finger blood flow. In line with the literature, stimulus magnitude, frequency and duration affected finger blood flow, especially in the index finger.

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Workers who use hand-held vibrating tools may experience finger blanching attacks due to episodic vasospasm in the digital vessels. The whiteness of the digits is the visible sign of an abrupt interruption of blood flow through the finger<sup>1</sup>. This phenomenon was first described by Raynaud in 1862 in a group of patients with peripheral vascular disorders of various origins. In occupational medicine, Raynaud's phenomenon caused by exposure to hand-transmitted vibration is also called vibration induced white finger (VWF) and is a prescribed disease in many countries.

The findings of experimental investigations of both normal subjects and patients with VWF suggest that the reduction in finger blood flow, finger skin temperature and finger blood pressure may depend on the frequency, magnitude and duration of the vibration stimulus<sup>2–6</sup>. All such factors thus need to be taken into account when assessing the probability of adverse effects in the digital vessels<sup>7</sup>.

Other studies have explored the vibration dose, individual and biodynamic factors, and the absorption/transmission of mechanical power to different parts of the human hand-arm system in relation to the grip and feed forces applied<sup>8–12</sup>.

The aim of the present study was to investigate how the haemodynamic effects induced on the digital arterioles by a hand-held hydraulic breaker related to different grip forces and to the vibration magnitude transmitted to the dorsal surface of the hand. Two novel instruments<sup>13, 14</sup> were used: a laser scanning Doppler vibrometer (LDV), whose laser beam was focused on the knuckles of the four long fingers to detect the vibration of the underlying

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soft tissue, and a polymeric capacitive sensor matrix wrapped around the handlebar, which measured the total grip forces and the spatial distribution of the pressure applied<sup>15</sup>. The merit of the proposed method is to allow simultaneous measurement of acceleration in operative conditions without contact by using the laser Doppler vibrometer, and of the grip force exerted by the operator's hand on the handle by using a capacitive sensing matrix. Compared with conventional apparatuses, its advantages lie in the possibility of avoiding the measurement problems caused by single-point accelerometers. In addition, the grip force is not estimated by a single force cell, as in many set-ups presented in the literature, but it is calculated as the sum of all the contact forces exerted by the operator's hand on the handle and measured by the pressure matrix.

## Subjects and Methods

### Subjects

Ten young healthy male volunteers, all Caucasian, were exposed to hand-arm vibrations by asking them to operate a hydraulic breaker. The study design was approved by the ethical committee of the Polytechnic University of Marche Medical School, Ancona.

The mean age of the subjects was 26.1 yr (SD 1.6); their height ranged from 172 to 186 cm (mean 180.8 cm, SD 4.9); weight ranged from 63 to 84 kg (mean 74.7 kg, SD 7.2) and body mass index ranged from 20.7 to 24.8. All subjects were students with no history of regular use of hand-held vibrating tools in occupational or leisure activities; all were non-smokers and reported mild alcohol consumption. None reported cardiovascular or neurological disorders, dysmetabolic or connective tissue diseases, injuries or surgical operations to the upper limbs, or a family history of Raynaud's phenomenon. Each subject gave his written informed consent to participate in the study.

Subjects were requested to abstain from caffeine and alcohol consumption for 2 and 12 h before the tests, respectively.

### Measurement of physical parameters

The following physical quantities were measured during the tests.

- Rms of hand surface vibration velocity maps in Z direction (orthogonal to the skin surface), with a laser scanning Doppler vibrometer.
- Handgrip pressure distribution and total grip force applied, with a capacitive sensor matrix wrapped around the handlebar<sup>14, 15</sup>.
- Rms handle acceleration in X, Y, Z directions, with three piezoelectric accelerometers mounted on the handlebar according to the relevant standards for hand-arm vibration.
- Vertical load force applied, with a platform scale on

which the operator was standing.

LDV data were compared with those yielded by the piezoelectric accelerometers in a previous investigation of the vibration transmitted to the hand-arm system by a pedestrian-controlled tractor<sup>13</sup>.

Rms acceleration magnitude was reported as frequency-weighted acceleration according to the ISO 5349 standard.

Subjects were required to operate the breaker in typical operative conditions for 5 min holding it with a subjectively low and high grip on separate days (sessions 1 and 2), and to apply a constant vertical load equal to 200 N ( $\pm 1$  N).

Visual control of the downward force applied to the handle was supplied by the platform scale. Force intensity was evaluated (in N) by the comparative sensor matrix: its scan rate of 0.5 Hz allowed a full pressure map to be made and measurement of the grip force to be produced every 2 s.

The grip force  $F_{gr}$  generated by the whole hand on the handlebar was calculated as:

$$F_{gr} = \sum_i F_{c,i} = \sum_i p_i S_i$$

where  $p_i$  is the pressure measured by each of the pressure matrix sensors (the matrix is composed of 256 sensors) when it is wrapped around the handle and the subject is operating the vibrating tool;  $S_i$  is the single sensor contact area (61 mm<sup>2</sup>) and  $F_{c,i}$  is the intensity of the force generated on the sensor  $i$ .

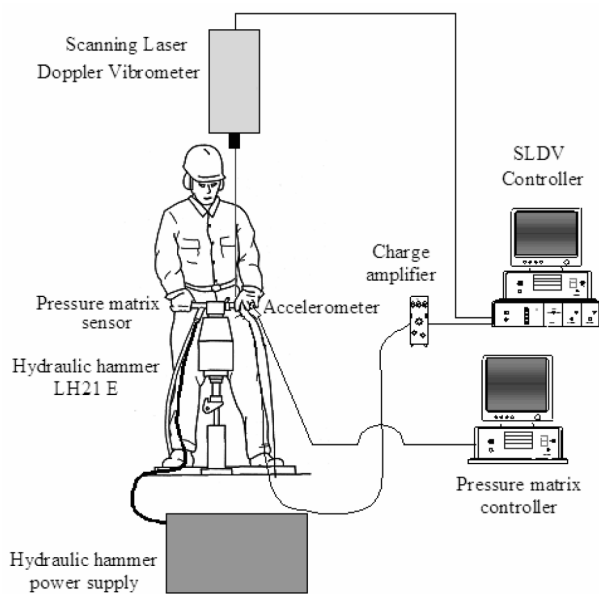
During the tests, the LDV was focused on the knuckles, where the skin is thin and taut, and measured their vibration velocity. It also detected the vibration of the handlebar, which was equipped with an accelerometer.

We calculated mean grip force as well as mean acceleration values, i.e. the sum of the single values recorded by the LDV on different points of the hand surface during the tests.

### Experimental procedure

The experiments were carried out at the laboratory of mechanical engineering of the University. The room temperature, measured by a mercury-in-glass thermometer to an accuracy of 0.1°C, was 22.7 (SD 0.6) and 22.4°C (SD 0.8) on the two days, respectively.

Subjects were randomly assigned to perform the tests on two separate experimental sessions held 1–7 d apart. At the time of each test, they had been sitting on a chair with their arms on the armrests at about the level of the heart for 20 min, before using the breaker, whose fundamental frequency was 27.5 Hz; and they wore light indoor clothing and headphones. The breaker was an LH21 E hydraulic hammer 682 mm in length, weighing 21.3 kg; the diameter of the handle was 38 mm. A sketch of the experimental set-up is shown in Fig. 1.



**Fig. 1.** Experimental and measurement set-up.

Measurements of blood pressure, heart rate, finger skin temperature (FST) and finger blood flow (FBF) were taken after this period of adaptation, immediately after exposure, and repeatedly until recovery of baseline values. Machine condition and operator posture were those envisaged by standard EN 709.

#### *Measurement of finger circulation and finger skin temperature*

FBF was measured in the four long fingers of both hands by distal pulp photoplethysmography, which detects the spasm or closure of digital vessels<sup>16, 17</sup>, by using a ULP 85 Gutmann photoplethysmograph equipped with a single-channel cold light photoreceptor. The apparatus was automatically calibrated; the speed of the recording paper was 25 mm/s.

A photoreceptor was attached to the pads of the four long fingers of each hand with adhesive tape and at least four pulse oscillations were recorded<sup>16</sup>. Measurements were taken in basal conditions, immediately after vibration exposure, and repeatedly until recovery of baseline values. The amplitude height of the photoplethysmographic (PPT) pulse waves was measured in mm. PPT wave amplitude has been demonstrated to be proportional to skin blood flow (ml/min) under the surface of the photoreceptor<sup>16-19</sup>.

The tracings were read by a vascular pathologist to avoid misinterpretations.

The effects produced by the sole grip forces were evaluated with the same protocol, by carrying out the tests in the absence of vibration (static load) also on two different days.

Brachial systolic and diastolic blood pressure (mmHg) and heart rate (hb/m) were measured on the upper right arm at the beginning and end of each experimental session by an auscultator technique with a standard pressure cuff.

FST was measured with an E 8105 thermocouple thermometer (Cole-Parmer Instruments) to an accuracy of 0.5°C. The use of this method to measure peripheral vascular reactivity is based on the assumption that FST depends on the rate of blood flow through the skin<sup>20-22</sup>.

FST was measured in basal conditions and after each test with the thermocouple probe fixed to the distal phalanx of each finger.

#### *Statistical analysis*

Data analysis was performed with SPSS-PC software. The data were summarised with the mean as a measure of central tendency and standard deviation as a measure of dispersion. The difference between two means was tested with the paired Student's t test. The statistical power of the t paired test was calculated with the Primit software (Biostatistics in Medicine, Stanton A. Glantz ed., 1981). Preliminary experiments were carried out on 10 subjects to evaluate the accuracy of PPT and thermometric measurements in basal conditions and after a cold provocation test of the hands, which induces vasospasm in digital vessels and skin temperature reduction.

Pearson's correlation coefficient was used to measure the strength of the association between two variables to establish the possible presence of linear relationships between the physical parameters and between the variations in the PPT amplitudes and the accelerations recorded on the hand surface. A p value of 0.05 was chosen as the limit of significance.

#### **Results**

All subjects were normotensive and their heart rate was 60–80 beats/min before the tests.

There were no significant differences between baseline pressure and heart rate measured on the two testing days, nor between the same parameters before and after the static load tests (not shown). By contrast, values increased significantly after exposure to vibration: heart rate increased significantly from 75 (1.25 Hz) to 89 hb/m (1.48 Hz) and from 73 (1.22 Hz) to 84 hb/m (1.40 Hz) for the low and high grip, respectively. Variations in mean systolic and diastolic pressure for low and high grip before and after exposure are shown in Table 1.

#### *Physical parameters*

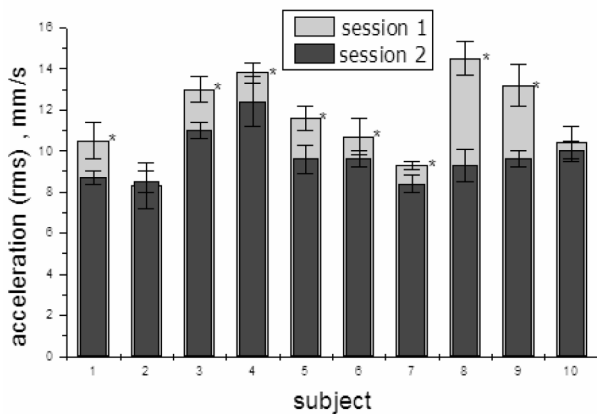
The mean values of grip force ranged from 59.7 to 169.2 N with the low grip and from 140.4 to 338.0 N with the high grip, as each subject had been instructed to hold the breaker based on his physical strength.

Handle rms acceleration values (Fig. 2: 32

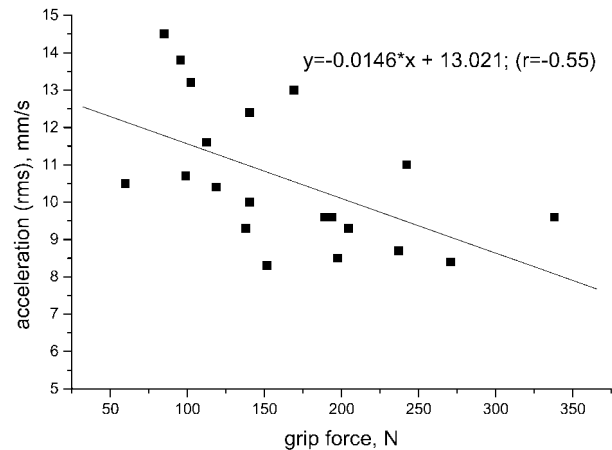
**Table 1.** Mean and standard deviation (SD) of systolic and diastolic pressure (mmHg)

	Systolic	Diastolic
Baseline	122.5 (SD 12.7)	77.5 (SD 6.8)
After exposure-low grip	135.5 (SD 13.4)*	83.5 (SD 8.2)*
Baseline	120.2 (SD 11.9)	77.2 (SD 5.5)
After exposure-high grip	132.7 (SD 12.8)*	81.8 (SD 5.7)*

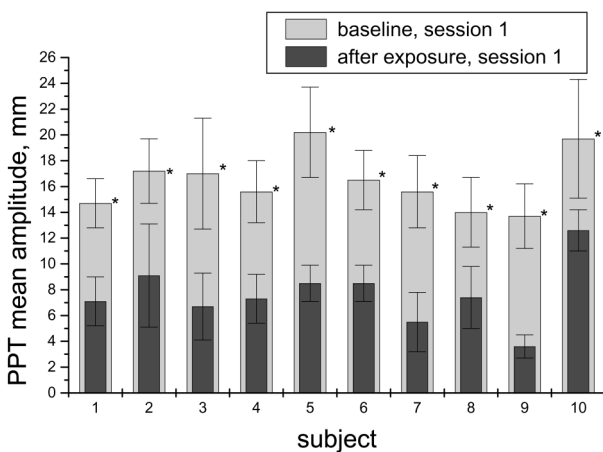
\*:  $p < 0.05$  (t-test for paired data, baseline vs. exposure).



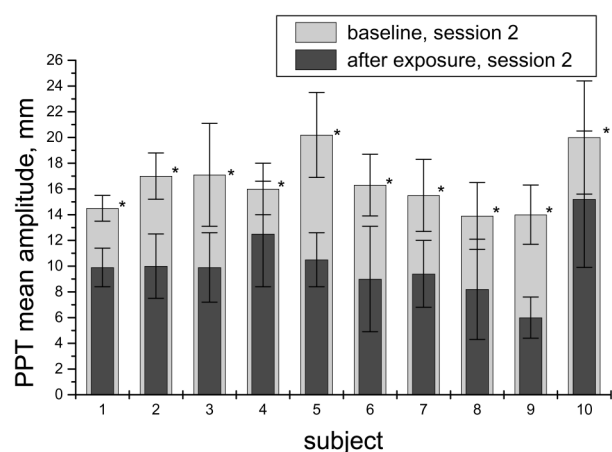
**Fig. 2.** Acceleration (rms), session 1 (low grip) and session 2 (high grip) - (\*:  $p < 0.05$ , t-test for paired data, session 1 vs. 2)



**Fig. 3.** Correlation between acceleration (rms) and grip force.



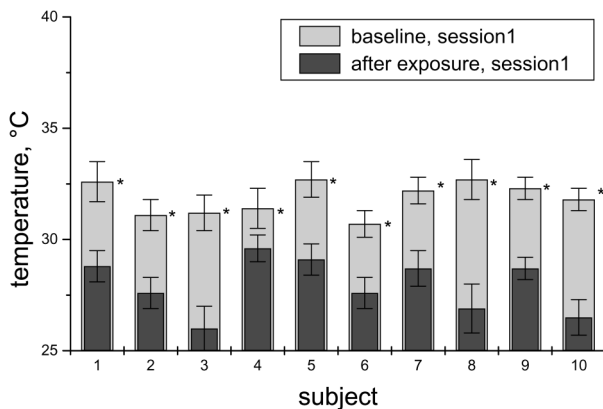
**Fig. 4.** Mean amplitude value for PPT waves (in mm) in the four long fingers and the two hands—Session 1 (low grip), (\*:  $p < 0.05$ , t-test for paired data, baseline vs. exposure).



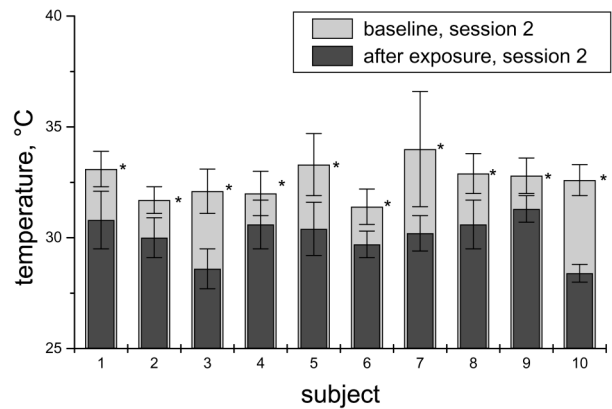
**Fig. 5.** Mean amplitude of PPT waves (in mm) in the four long fingers and the two hands—Session 2 (high grip) (\*:  $p < 0.05$ , t-test for paired data, baseline vs. exposure).

measurements averaged for each acceleration value, 10 subjects, 2 grip conditions, = 640 samples) were significantly higher in the tests with the low grip except for two cases (Nos. 2, 10).

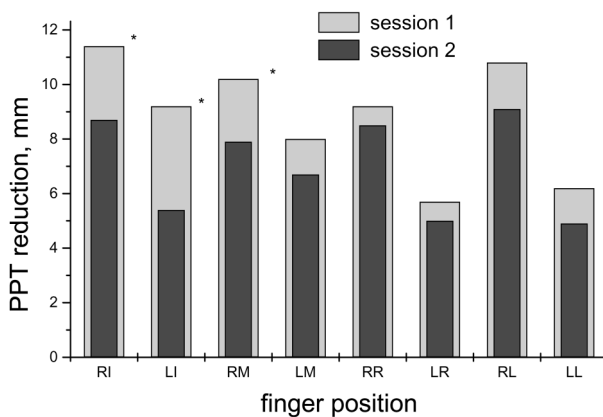
The relationship between accelerations and grip force was found to be linear ( $y(=acceleration) = -0.0146x(=force) + 13.021; r = -0.55$ ), and such that an increase in grip strength was accompanied by a reduction



**Fig. 6.** Mean finger temperature in the four long fingers and the two hands—Session 1 (low grip) (\*:  $p < 0.05$ , t-test for paired data, baseline vs. exposure).



**Fig. 7.** Mean finger temperature in the four long fingers and the two hands—Session 2 (high grip), (\*:  $p < 0.05$ , t-test for paired data, baseline vs exposure).



**Fig. 8.** PPT reduction (= [baseline]–[after exposure]) measured in each of the four long fingers of the two hands in basal conditions and after vibration exposure in the two sessions (RI: right index finger, LI: left index finger; RM: right middle finger; LM: left middle finger; RR: right ring finger; LR: left ring finger; RL: right little finger; LL: left little finger) - low and high grip (\*:  $p < 0.05$ , t-test for paired data, PPT reduction session 1 vs. PPT reduction session 2).

in the amplitude of the accelerations transmitted, whereas a lower grip resulted in its increase (see Fig. 3).

*Finger blood flow and finger skin temperature*

Baseline PPT values<sup>23)</sup> and finger surface temperature<sup>24)</sup> were in the normal range.

After vibration exposure, the amplitude of the PPT waves was always significantly lower than the baseline. Similarly, the superficial finger temperatures recorded after each test were significantly lower than the baseline.

The means and standard deviations of PPT wave and temperature values measured in the four long fingers

during the two sessions are shown in Figs. 4–7.

Measurements were performed until recovery of baseline values, which consistently occurred within 5 min of cessation of exposure. The wave amplitude of each finger and hand was significantly reduced after both tests day. The reduction (= [baseline]–[after exposure]) was especially marked after the test with the looser grip, although significant differences were found only in the index finger and in the right middle finger (Fig. 8). These data were obtained by averaging 4 values for each PPT measurement on 8 finger positions before and after vibration, for each subject, for low and high grip (640 samples).

Application of the sole static load also produced significant decreases in finger blood flow during both tests without vibration; in these cases, however, values returned to baseline within 30 s of release without significant hyperhaemic rebound (not shown).

**Discussion**

The novel apparatus used in this study<sup>13, 14)</sup> made it possible to measure the intensity of the grip force applied to the handlebar and the accelerations transmitted to the hand.

The broad range of forces applied by the subjects reflects the specific ability of each to exert the required force. Indeed, some subjects held the handlebar with a high grip that was similar to the low grip measured in other subjects (Nos. 4, 10 and 3, respectively). This result is not surprising considering the inherent interindividual variation and the fact that we used a real hydraulic breaker. In addition, it would be extremely difficult for a subject to repeat the test applying an identical grip force. Our tests aimed at measuring the vascular effects produced by two different conditions, the low and the high grip, assuming non-constant grip force and acceleration

magnitude as in real operative conditions for such tools. Similar experimental conditions have been reported by Kinnie and Melzing-Thiel<sup>25</sup>.

Analysis of the values recorded in the two tests showed that the grip was linearly related to the transmission of accelerations ( $r=-0.55$ ).

The data reported by Hartung and co-workers<sup>20</sup> and by Riedel<sup>26</sup>, who measured greater accelerations at the wrist, elbow and shoulder with a higher grips are ostensibly at variance with ours. Since in the present study accelerations were measured at the knuckles, the methods do not appear to be homogeneous. Nonetheless, it may be hypothesised that a greater amount of the resonant vibrations produced by our hydraulic breaker, which are predominantly low-frequency, are transmitted to the wrist, elbow and shoulder when the tool is held with a high grip force, whereas they remain confined at the level of the hand, with greater vasoconstriction effects recorded in the fingers, when a relatively low grip force is applied.

The relationship among grip force, the energy absorbed by the hand-arm system measured in terms of hand-transmitted force, and the speed of the latter has also been studied by Burström and colleagues<sup>8, 9, 11, 27</sup> on an electrodynamic shaker, which produces sinusoidal vibration. At frequencies higher than 75 Hz, Burström and Lundström<sup>27</sup> generally observed a positive non-linear correlation between absorbed energy and grip force<sup>9</sup>. When the latter was between 25 and 50 N, the absorbed energy increased by a factor of 1.3, and between 50 and 75 N by only 1.1.

In the present case, with a different experimental model, all subjects but No. 1 employed a grip force greater than 75 N and the first operating frequency of the hydraulic breaker was 27.5 Hz.

Our results confirm previous studies indicating that acute exposure of the hand-arm system to vibration causes a blood flow reduction in finger arterioles and in finger skin temperature<sup>1, 2, 4, 7, 24, 28-30</sup>. Different durations and modes of exposure result in different vasoconstriction effects arising in different ways and lasting for different lengths of time<sup>1, 29, 31</sup>. A greater reduction in FBF after the test with the low grip occurred in both index fingers and in the right middle finger in 6 subjects, who were probably more susceptible than the others.

The vasoconstrictive effects observed in the present study with a high and a low grip in the absence of vibration are also in line with reports of reduced blood flow after the application of grip force only<sup>18</sup>. Such effects disappeared within 30 s of test cessation, whereas the vasoconstriction induced after the tests with vibrations lasted longer.

These observations appear to be consistent with the findings of several other studies, where the vasomotor effects induced by vibration, hence arteriolar blood flow,

have been seen to depend on the amplitude of the accelerations transmitted to the hand surface<sup>7, 30-32</sup>. Increasing vibration magnitude, measured by an increase in root mean square acceleration magnitude, has been seen to enhance FBF reduction<sup>7, 31</sup>. Similar results are produced by increased duration of hand-transmitted vibration<sup>28</sup>, whereas FBF recovery is delayed by increased vibration intensity<sup>33</sup>.

In conclusion, and in line with the literature, with our apparatus the amount of FBF reduction induced by subjects exposed to vibrations generated on hand-held tools depends on several parameters such as magnitude and frequency of the vibratory stimulus, duration of hand-transmitted vibration and individual biodynamic factors.

By measuring the accelerations and the pressure applied to the handlebar with a novel apparatus, our study showed that grip force is an additional factor influencing FBF because less hand-transmitted accelerations and less vasoconstriction effects were observed with the higher grip.

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