EXECUTIVE SUMMARY OF THE THESIS

Effects of whole-body vibration on walking kinematics and cognitive response

TESI MAGISTRALE IN BIOMEDICAL ENGINEERING – INGEGNERIA BIOMEDICA

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1. Introduction

Interest in the effects of whole-body vibration (WBV) has over time grown through studies that have demonstrated its impact on health. As a result, directives, such as Directive 89/391/EEC, have been created that indicate and suggest technical precautions to minimize the level of vibration exposure. The risk does not disappear entirely; in fact, about 24 percent of workers in Europe are exposed to mechanical vibration. Nowadays, WBV is the fifth most common occupational disease in Italy [1]. In addition, to the damage from the physical point of view, it is of growing interest how vibration changes the cognitive response. Inattention, fatigue, memory shortening and other symptoms are equally impactful on health, so it is equally important to study their correlation with vibration.

2. State of the art

If people are subjected to vibration for a prolonged time, the health consequences can be physical and psychological fatigue, musculoskeletal disorders, vascular and nervous disorders [2]. Assessment is based on how the oscillatory motion is applied: we can distinguish them into Whole-body vibrations (WBV), Hand-Arm Vibrations (HAV) and Foot Transmitted Vibration (FTV). Following the demonstration of WBV damage, daily exposure limits were imposed by European Directive 2002/44/EC.

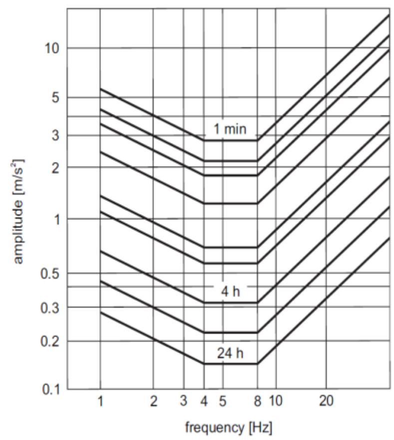

Figure 1: Daily limit exposure at vibrations

2.1 Pathologies related to WBV

It is important to divide vibration damage into musculoskeletal and cognitive. The former is caused by exposure through power or pneumatic tools or by driving transportation, construction, or agricultural equipment. The main disorders are related to spinal damage, low back pain, herniated discs, and sciatica [3]. It has been studied that as the years of exposure increase, the percentage of risk of disability increases. Workers in the seafood industry are also subject to WBVs generated by engines or boat motion, in which case they may be exposed to impact or shock vibration that causes spinal, knee and hip injuries [4].
From a cognitive point of view, the response to auditory and visual stimuli is often studied, which has shown an increase in reaction time. In other cases, WBVs cause an increase in reading time [5] or a decrease in attention threshold [6]. Other possible consequences are identified as: increasing drowsiness, loss of consciousness, sleepiness and an increase in process time. However, the effects can also be beneficial, such as for the case of adults with attention deficit hyperactivity disorder (ADHD) [7] and for those suffering from traumatic brain injury (TBI) [8].

2.2 Evaluation of vibration's effects

From a kinematic point of view, it has been noted how subjects in a standing position behave differently depending on the support (normal, bent legs, on one leg), or the degree of knee flexion. The closer one gets to a stable position relative to the direction of vibration propagation, the less vibration will propagate in the body. The perturbations given by WBV change the subject's stability and gait parameters. These evaluations, in the case of kinematics, can be carried out by optoelectronic systems, electromagnetic systems or inertial sensors. The former represents the gold-standard, but they are very expensive systems, require laboratory space and skilled operators. Electromagnetic sensors track three-dimensional coordinates and require neither markers nor large spaces, but are sensitive to magnetic fields. Finally, IMUs (Inertial Measurement Units) can determine the dynamics of an object with a 3D gyroscope, angular velocity meters, 3D Accelerometers and a barometer.

Evaluation in the case of cognitive stimulation is done by measuring reaction time. What changes from one study to another are the tasks to be performed during the experiment. Some studies used visual stimuli, pressing a key or combination of keys based on what appeared on a monitor, others to indicate whether a symbol or letter was part of previously seen figure sets, with the aim of assessing short-term memory.

3. Aim

The purpose of this thesis is to evaluate how five different frequencies of WBV_{LS} may affect the kinematics and cognitive response of subjects while walking. A total of 41 healthy subjects were considered for the study; for kinematic data collection we focused on the lower limbs and for cognitive data on a reaction test. The experimental trials involved six walking sessions on a treadmill subjected to 6 different vibration conditions (0 - 2 - 4 - 6 - 8 - 10 Hz) at a constant speed. Three acquisition systems were used: 2 for kinematics and 1 for reaction time. Lower limb movements were collected with a marker-based optoelectronic system (BTS Bioengineering) using 32 reflective markers placed at specific anatomical positions and an inertial sensor system (Xsens Awinda), with 7 probes. The reaction test is called the 'psychomotor vigilance test' (PVT), which consists of placing a system of diodes that when illuminated green tell the subject to press a trigger that marks the reaction time.
Values of interest for the study were identified as: ankle eversion and flexion angles, knee flexion angles, hip flexion and abduction angles, stride length and frequency. For the assessment of cognitive response, reaction time was considered.

4. Materials and methods

4.1 Materials

The set-up, shown in Figure 2, required a space exclusively for testing. The components used during the tests are a 'Xiaomi WalkingPad A1' treadmill with a remote control, a 'Keysight 33220 A' shaker that generates sine waves and connected to a motor causes the treadmill to oscillate laterally, a 'BTS Smart DX-400' optoelectronic system for motion analysis, XSENS system for a second kinematic analysis, and a Psychomotor vigilance test 'PVT'.

Figure 2: Experimental set-up

The BTS system used included six infrared cameras and 32 reflective markers. The XSENS Awinda system used consisted of Velcro strap bands to keep the seven sensors used on lower limbs and pelvises properly positioned. The reaction test, on the other hand, consists of two sets of LEDs, one part illuminates green, the other blue; the visual stimulation device is connected to a button held by the subjects during testing.

4.2 Methods

The experimental protocol was proposed by Prof. M. Tarabini and was approved by the ethics committee. It is specified that the duration of the tests is not intended to create fatigue, but to allow changes in kinematic and cognitive response. Subjects are to perform the tests six times while walking subjected to WBVL for a total exposure time of 20 minutes. The measured parameters, both with and without vibration, are:

- Cognitive reaction time
- Frequency, length and amplitude of stride
- Kinematic parameters of whole-body gait, including flexion, extension, rotation, abduction and adduction
- Acceleration of vibration exposure

For each subject, the test takes 35-40 minutes including preparation. For each of the six tests, one for each frequency (0-2-4-6-8-10 Hz), the examinee will have to walk at 4.5 km/h (1.25 m/s) for about 3.5 minutes. The sequence of frequencies to which each is subjected was randomized before the tests began so as to combine vibration frequency and amplitude:

- PVT 0 – 0 Hz, 0 mm amplitude
- PVT 1 – 2 Hz, 18 mm amplitude
- PVT 2 – 4 Hz, 4.5 mm amplitude
- PVT 4 – 6 Hz, 2.0 mm amplitude
- PVT 5 – 8 Hz, 1.1 mm amplitude
- PVT 6 – 10 Hz, 0.7 mm amplitude

In addition to the legal aspects, height, weight, and foot length are required to be entered as parameters in the IMU sensor software.

Participation of subjects in the experimental trials is voluntary. 41 volunteers, 21 males and 20 females, between the ages of 18 and 50 and who do not have any of the following conditions were eligible to participate:

- Lower extremity injuries in the previous 6 months
- Lingering symptoms from past orthopedic injuries
- Current or past long-term WBV exposure
- Cognitive disabilities of developmental disorders
- Previously diagnosed by a physician to have diabetes
- Present or past vibration-induced pathologies
- Ever experienced a concussion
- Suffer from motion sickness
- Current or past neuromuscular or neurological pathologies
- Allergy to adhesive for markers

Preparation of each subject required 10-15 minutes for application of the 32 markers and 7 IMU sensors. Once applied, the subjects looked as in Figure 3.

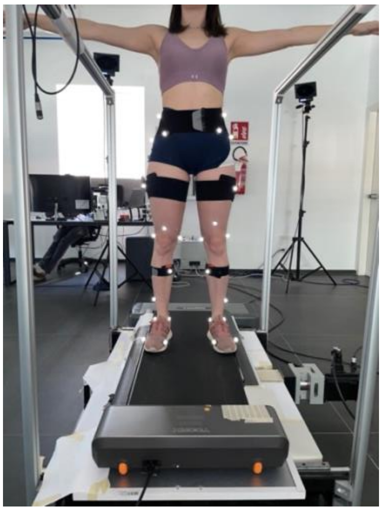

Figure 3: Calibration position with all sensors in place

After the optoelectronic system calibration, 32 markers have to be applied on lower limbs and shoes according to the 'modified plug-in-gait marker set' protocol. Post-processing of the collected data is done using the SMART Tracker software, which once the model is imported allows reconstruction of the gait kinematics.

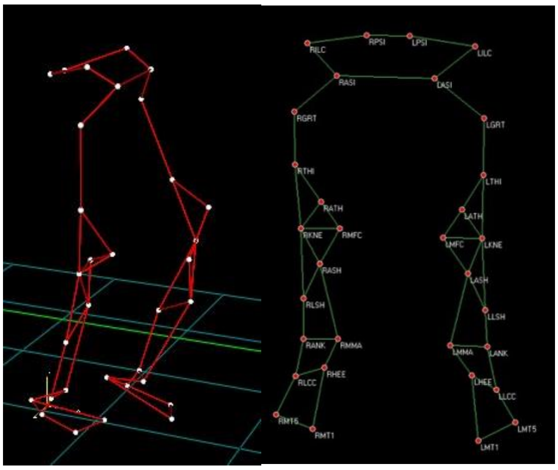

Figure 4: Lower limb reconstruction and marker positioning model

IMUs also need to be calibrated before testing. For each subject is calculated the number of steps and for each of them the degrees of rotation in the plane of the corresponding movement. This data are stored in a MATLAB structure in which each subject has step and angle data for each frequency and joint. For each step, the Range of Motion (RoM) is calculated as the subtraction between major and minor angle. Elimination of outliers using the 'IQR 1.5' method is performed before calculating the mean and the standard deviation.
To collect cognitive data, the walking subject should press the handheld button as soon as the green light up. The time elapsed between lighting the green LEDs and pressing the button is recorded by MATLAB, after which the test starts again. This process continues for three minutes until 30 reactions occur. The reaction times are stored in a MATLAB structure and is performed the same outlier elimination test ('IQR 1.5') before computing mean and standard deviation.

5. Results

5.1 Cognitive response

To find a dependence between WBV_L and cognitive response, a two-way Anova repeated measure was performed. To have a statistically significant difference, compared to the base case of 0 Hz, the p-value found must be less than an alpha value, on which the Bonferroni correction is made. The results are shown in Table 1.

Term	F-Value	P-Value
Freq (Hz)	1.46	0.203

Table 1: Fixed Effects PVT

As is immediately noticeable none of the p-values is less than 0.01, which means the there is no correlation between reaction time and frequency.

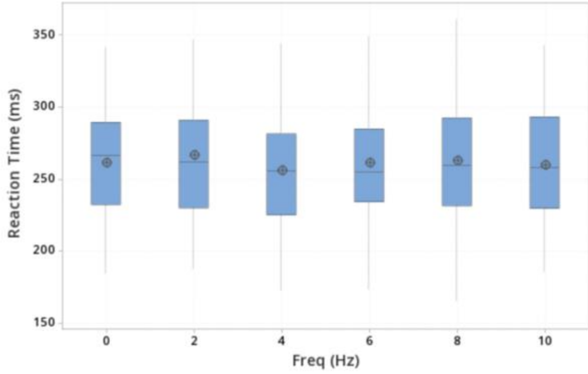

Figure 4: Boxplot reaction time vs frequence

The graph confirms the previous results, in fact it is evident how the median of each frequency does not stray too far from the case with 0 Hz.

5.2 Kinematic response

As for the cognitive response, the Mixed effect model was run for dependent variable in which the frequency was considered as a fixed factor and the intrinsic variability of the subjects is considered as random factor.

Term	Variable	F-Value	P-Value
FREQUENCE	AR Flex	4.98	*0.000*
	AL Flex	3.43	*0.006*
	KR Flex	5.77	*0.000*
	KL Flex	6.85	*0.000*
	HR Flex	0.95	*0.448*
	HL Flex	3.83	*0.003*
	HR Abd	12.18	*0.000*
	HL Abd	5.72	*0.000*
	AR Inv	0.59	*0.708*
	AL Inv	1.25	*0.287*
	Stride freq	22.72	*0.000*

Stride length	21.49	*0.000*

Table 2: Mixed Effects Model

Table 2 show the joints in which at least one pair of frequencies, compared with each other, are statistically relevant. In the case of P-Value less than 0.05 a Bonferroni simultaneous test is performed. In this way, every frequency is compared with the 0 Hz case. In the following tables are shown which pairs are relevant (adjusted P-value < 0.05). This test resulted in 0 - 2 Hz pairs being statistically significant specifically for: bilateral ankle and knee flexion, left hip flexion, bilateral hip abduction, step length, and step frequency. The following table shows the results.

Variable	Freq	Difference of Means	Adjusted P-Value
AR Flex	2 - 0	-1.838	0.003
AL Flex	2 - 0	-1.329	0.024
KR Flex	2 - 0	-2.071	0.001
KL Flex	2 - 0	-2.680	0.000
HL Flex	2 - 0	-0.843	0.007
HR Abd	2 - 0	-1.381	0.000
HL Abd	2 - 0	-1.148	0.003
Stride freq	2 - 0	0.03065	0.000
Sride Length	2 - 0	-0.04858	0.000

Table 3: relevant Bonferroni tests results

6. Discussion

6.1 Cognitive response

No changes in reaction time were found between the six frequencies and the 0 Hz case during walking subjected to WBV_L. In fact, the 'tests of Fixed Effects', Table 1, shows a p-value much greater than the 0.01 threshold. Since no statistical significance was found, we did not proceed in the comparison of each frequency with the base case of 0 Hz. Results confirmed by some studies, for example Marelli [9] studied that statistical significance is found only for frequencies below 2 Hz. In other articles, it is highlighted 4 Hz frequency as the main reason on increasing reaction time, but the set-up was built different (the subject was sitting instead of standing).

6.2 Kinematic response

From the results, it was noted that nine of the 12 cases considered showed sufficient variability to deepen the comparison between the frequencies and the base case. For all cases considered, Bonferroni's test shows that a statistically significant difference there is between the 0 - 2 Hz pair. This case is significant because this frequency corresponds to the maximum amplitude of the vibration, i.e., the treadmill oscillation is larger. It transpires from the results that hip flexion, due to the constitution of the joint itself, does not exhibit a significant change in RoM. In fact, the changes that the body makes to cope with vibrations depends on their direction of propagation [10]: hip flexion has no effect on medial-lateral stability, on the opposite hip abduction increase it.

The importance of this study is given from the need to create new methods of evaluating the effects of vibration and expand the guidelines governing vibration exposure. In fact, ISO 2631-1 determines how to evaluate WBVs applied mainly to seated persons since the health effects of people in standing, recumbent or reclining positions are not known. Similarly, the Directive 89/391/EEC indicates minimum requirements for the health and safety of workers, always limiting itself to the sitting position. Thus, the results reported here can be seen as the beginning of the creation of new rules for establishing the effect of horizontal whole-body vibration on walking subjects.

7. Conclusion

Statistical analysis, aimed at finding a correlation between exposure to vibration of different frequency and amplitude and the normal walking case (without vibration), shows two different results. Reaction times show no statistically significant results, meaning that for the task proposed to the subjects and the frequencies they are exposed to, they do not show a decline in attention. On the other hand, analysis of joint ranges of motion and step characteristics, frequency and length, show strong dependence with the 2 Hz frequency. The search for the effects of WBVs, required in this study, is not limited to statistical significance, but to demonstrating instances where movement changes significantly (range of motion has to be greater than |1|). The results, therefore, provide insight into how the body modifies its behavior to adapt to external perturbations. In this way, new aspects related to vibration exposure can be explored.

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