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

TESI DI LAUREA MAGISTRALE IN
BIOMEDICAL ENGINEERING

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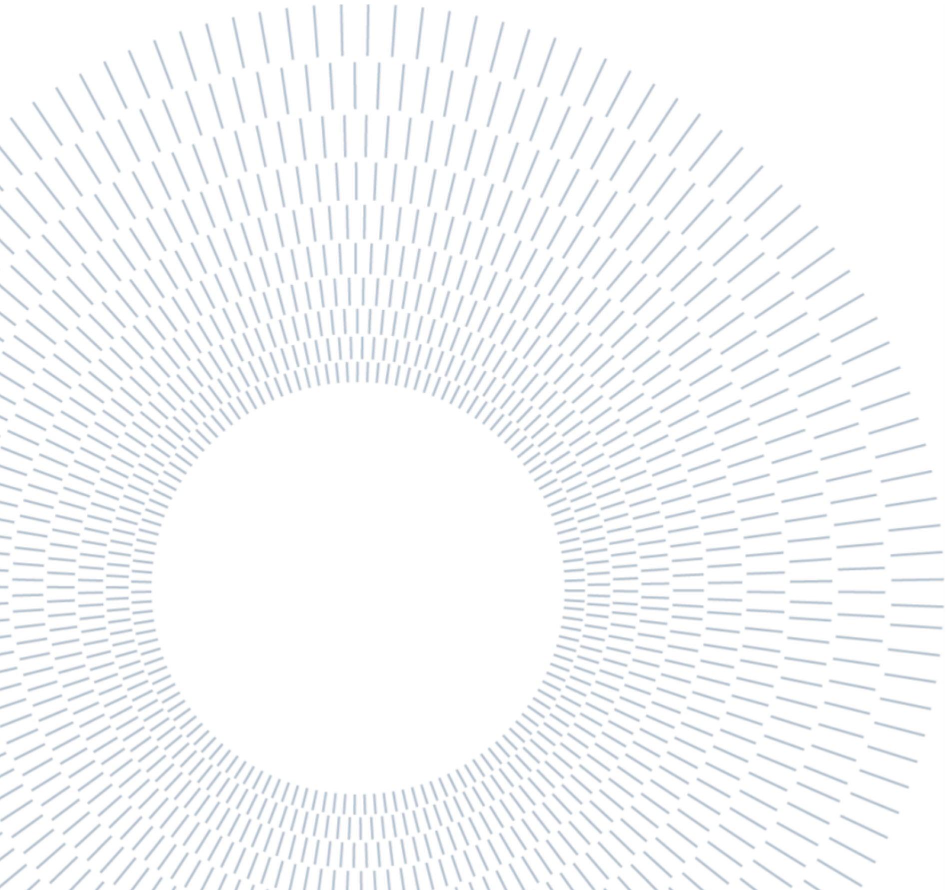


Abstract

Nowadays, several people are subjected to vibration either directly or indirectly. Workers in the manufacturing, transportation and fishing industries are most affected by them. This background gives rise to an interest in finding out how vibration affects health.

In this thesis, it is shown how whole-body vibrations, with lateral propagation with respect to the direction of gait, modify gait kinematics and reaction time to visual stimuli. An experimental set-up consisting of three acquisition systems: marker-based optoelectronic, inertial motion capture system and reaction test was used to analyze the behavior of individuals subjected to vibrations. Data from the last two systems were analyzed, so that both kinematics and cognitive response were matched. Volunteer subjects participating in the test are asked to walk on a treadmill for about 25 minutes, 20 of which are subjected to whole-body lateral vibrations. The selected sample consists of 21 men and 20 women, whose results were fully used for reaction time analysis, and a sample of 31 subjects for kinematic evaluation. The frequencies considered of interest are 2, 4, 6, 8, 10 Hz, with relative decreasing amplitudes, are compared with the case at 0 Hz.

The question that, this thesis aims to answer is what frequency and how much it changes the gait kinematics and reaction time of those subjected to whole-body vibrations. Reaction time is shown to be unchanged for all vibrations, instead joints flexion and abduction, and stride length and frequency are shown to be significant enough to result in walking.

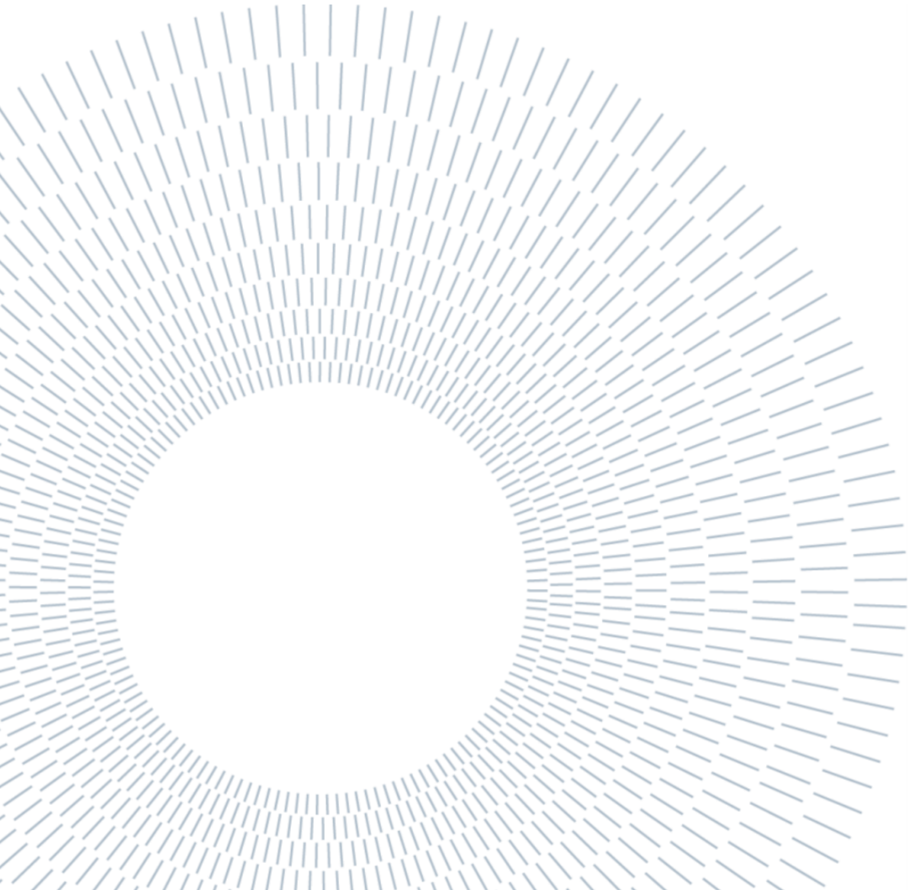
Key-words: Whole-body vibration, Walking, Lateral vibrations, IMU System, PVT

Abstract in lingua italiana

Al giorno d'oggi, gran parte delle persone è soggetta a vibrazioni sia direttamente che indirettamente. I lavoratori nelle industrie manifatturiere, trasporti e ittiche risentono maggiormente del loro effetto. Nasce in questo modo l'interesse di scoprire in che modo le vibrazioni influiscono sulla salute.

In questa tesi viene mostrato come le vibrazioni trasmesse a tutto il corpo (whole-body vibration) con propagazione laterale rispetto la direzione del cammino modifichino la cinematica del cammino e il tempo di reazione a stimoli visivi. Per analizzare il comportamento dei soggetti sottoposti a vibrazioni, è stato usato un set-up sperimentale composto da tre sistemi di acquisizione: optoelettronico su rilevamento di marker, sistema di rilevamento di movimento inerziale e test di reazione. I dati degli ultimi due sistemi sono stati analizzati, in modo tale da avere sia un riscontro nella cinematica sia nella risposta cognitiva. Ai soggetti volontari partecipanti al test viene chiesto di camminare su un tapis roulant per circa 25 minuti, 20 dei quali sono sottoposti a whole-body lateral vibrations (WBVL). Il campione selezionato è composto da 21 uomini e 20 donne, i cui risultati sono stati interamente utilizzati per l'analisi del tempo di reazione, e un campione di 31 soggetti per la valutazione cinematica. Le frequenze considerate di interesse sono di 2, 4, 6, 8, 10 Hz, con relative ampiezze decrescenti, sono confrontate con il caso a 0 Hz. La domanda che, questa tesi, ha come obiettivo di rispondere è quale frequenza e quanto modifica la cinematica del cammino e il tempo di reazione dei soggetti sottoposti a whole-body vibrations. Il tempo di reazione si dimostra invariato per tutte le vibrazioni; invece, flessione e abduzione delle articolazioni, lunghezza e frequenza del passo si dimostrano significative da comportare una variazione nella deambulazione.

Parole chiave: Whole-body vibration, Cammino, Vibrazioni laterali, Sensori IMU, PVT



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Introduction

As a result of several studies that report how whole-body vibration (WBV) leads to several diseases, interest in studying how they are caused and how to evaluate the impact of vibration has increased. The first indications regarding the effects of vibrations can be found in Directive 89/391/EEC, which suggests technical precautions to reduce to the lowest level the vibrations produced by machinery [1]. Subsequently, in 2002, Directive 2002/44/EC set minimum health and safety requirements, especially for vibrations, requested by the European Parliament in September 1990. The term whole-body vibration is defined as follows: "the mechanical vibration that, when transmitted to the whole body, entails risks to the health and safety of workers, in particular lower-back morbidity and trauma of the spine" [2]. Despite the decrease in areas requiring physical effort, the risks associated with vibration are still prevalent [3]. The sectors that are sensitive to vibration exposure are related to transport, agriculture, forestry, fisheries, construction, mining and manufacturing. Most of these workers are subjected to daily vibrations and on average between 10% and 20% miss days of work due to accidents [4]. WBV is directly associated with the development of diseases that include back and neck pain [5], cardiovascular disease [6], neuropathies [6], digestive problems [7], headaches, dizziness and motion sickness. Since 1990, the number of European workers exposed to mechanical vibrations has constantly been increasing, reaching an estimated 24% [8]. Similar results were obtained in Italy, where 26% of workers are exposed to mechanical vibration, and , in particular, 11% all the working time, 8% at least three-quarters of the time and 7% at least one-quarter of the time [3]. Nowadays, mechanical vibration is the fifth most common occupational disease compensated for in Italy [3]. ISO 2631-1 (1997) has been created in order to provide guidelines on how to properly measure and interpret WBV exposure in relation to human health and comfort [9]. This norm specifies how the human body responds differently depending on the direction of transmission and the frequency content of the vibration exposure [9].

In addition to the interest in how vibration affects comfort and health, several studies investigate how cognitive response changes when individuals are subjected to WBV. The general finding is that vibration produces decrements in cognitive performance, significantly poorer performance in short-term memory task [10], affects reaction time and increase drowsiness [11]. Since both kinematics and cognitive response significantly affect health, it is equally important to study their involvement and correlation in response to WBV.

1. State of the art

1.1 Vibration characteristics

People are exposed to vibration in most work and daily activities. If this occurs for a prolonged time, health consequences can occur physical and psychological fatigue, musculoskeletal disorders, and vascular and nervous disorders [12]. Vibrations are mechanical oscillations with respect to a reference point determined by pressure waves transmitted through solid bodies. In the case where vibrations are caused by external factors, then they are called forced: this is, for example, the case for workers. The parameters that go into defining vibration characteristics are frequency, amplitude, velocity, and acceleration. The frequency defines the type of vibration. Low-frequency oscillations are between 0.1 and 2 Hz and are those generated by land, air and sea transportation means; medium-frequency oscillations range between 2 and 20 Hz, generated by industrial machines and plants; and high-frequency oscillations, above 20 Hz, generated by vibrating industrial tools. The amplitude determines the maximum displacement from the equilibrium position. Velocity and acceleration determine the kinematic characteristics of the phenomenon. The latter is perhaps the most important parameter in assessing the bodily response to vibration, as humans feel more the variation of a stimulus than its persistence. Other equally important characteristics are vibration input regions and their direction, resonance, and exposure durations.

1.1.1 Types of vibrations

The evaluation of vibrations is analyzed differently depending on how they are applied. When these are applied to the whole body then they are called Whole-Body Vibrations (WBV), if they are transmitted from hand-arm, Hand-Arm Vibrations (HAV) and if from the feet, Foot Transmitted Vibrations (FTV). HAVs, which are of the localized type, are generated by tools in use in construction, metallurgy, metalworking, and woodworking because the use of vibrating tools is very common. FTVs, which are also localized, take effect when standing on vibrating platforms, on means of transportation, or by propagation of vibrations through the ground generated by machine tools. When the vibrations propagate throughout the body, in places other than hands and feet, or HTVs and FTVs are not limited to having effects only in the respective limbs, then we speak of WBVs. Again, the sources are similar to those in the previous cases.

1.2 Whole-body vibrations

Unconsciously, people are subjected to WBV every day through the use of transportation. This exposure can lead to health damage, not only physical but also cognitive [13]. The group most affected by the effects of vibration is workers, so once the harmful effects that vibration brings were demonstrated, EU Directive 2002/44/EC imposed daily exposure limits [14].

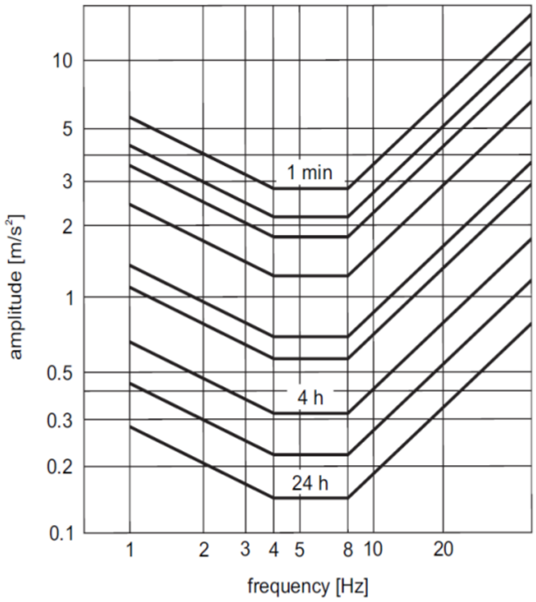


Figure 1: Daily vibration’s exposure limits suggested by ISO 2631-1 [15]

Evaluation of the effects of WBVs is performed not only on standing individuals, but also on seated, reclining or recumbent people, so the ISO 2631-1 standard defined vibration-related risks. The European directive suggest the daily exposure limit value standardized to an eight-hour reference period should be 0,5 m/s^2.

1.3 Pathologies related to WBV

It has been estimated that at least 24% of European workers are exposed to mechanical vibration, an increasing trend since 1990 [3]. The health and safety consequences of HAVs and WBVs have been evaluated in several studies. In particular, it is relevant to subdivide the possible vibration-related damages into musculoskeletal impairments and cognitive impairments. Epidemiological and experimental studies have shown that prolonged exposure to high levels of vibration can cause disorders and injuries mainly to the upper limbs and spine [16]. Moreover, regarding effects on cognitive performance, attempts are being made to demonstrate changes in reaction and concentration times.

1.3.1 Musculoskeletal pathologies

Currently, mechanical vibration is the fifth most common occupational disorder in Italy. Workers are exposed to vibration through the use of power or pneumatic hand tools or by driving large transportation, construction, or agricultural vehicles [4]. Recent studies have shown how vibrations can be transmitted through the platforms you are working on. The disorders that are most frequently highlighted are related to spinal disorders, low back pain (LBP), herniated discs, and sciatica [6]. It has been mainly found in professional drivers, such as transport or truck drivers, and warehouse workers that these effects are amplified as they add lumbar strain [17]. Sciatica presents with symptoms of pain, numbness, or tingling throughout the sciatic nerve distribution [18]. Back damage is not only localized to the lumbar section, but cases have been shown at the cervical level in helicopter pilots, probably caused by the weight of helmets and accessories leading to increased weight bearing down on the neck [19]. This is not the only problem pilots may face, as, like other similar professions, they are forced to maintain an often-uncomfortable position for long periods of time. Damage related to intervertebral disc disease, has been investigated in depth through studies related to crane operators, and it has been shown that as years of exposure increase, the percentage of risk of disability increases compared to a control group [20]. Workers in the fishing industry are also exposed to WBV generated by engines or boat motion, especially in rough waters. Under certain environmental conditions they may be exposed to impact or shock vibration that would result in injury of the spine, knees, and hips. Workers in this industry are often subject to fatigue, headaches and seasickness due to the movement caused by the waves [4]. Thus, workers in various manufacturing and non-manufacturing categories may suffer from back, neck and shoulder pain, migraine, dizziness, motion sickness, and the development of some chronic cardiovascular diseases, type II diabetes, metabolic disorders, or prostate cancer.

1.3.2 Cognitive pathologies

The influence of WBVs on cognitive abilities has been demonstrated by several studies that can be divided between those performed in a controlled environment, laboratory, and those in the field. With regard to the latter, the 'Omega Test,' which aims to study the consequences of WBVs on the health of drivers or operators, was found to be relevant [21]. Subjects, isolated in the back of a van, are given the task of moving a pointer along a curvy line using two knobs. During the recording, the growth of three parameters is noted: number of errors (NE), total time (TT) and total error duration (DTE). The DTE represents the time between the error and the correction, i.e., the displacement of the pointer from the edge of the path. The growth of these three values is closely related to the exposure to WBV [22]. Thus, it is relevant how negative impact affects the reaction time of people subjected to vibration. The time between receiving the stimulus and responding to it is composed of mentally processing information and performing physical operations. External phenomena, such as vibration, lead to an increase in both processing times [15]. Several studies have investigated how time variation is affected by WBV, while others have focused on visual and auditory stimuli. Particular interest has been given to frequencies near 5 Hz, since it has been identified as the resonance frequency of the body [23]. With individuals subjected to auditory and visual stimuli and subjected to vibration, reaction time decreases: the fatigue factor also takes over in these cases. In particular, reading speed was shown to decrease under the influence of horizontal WBV, counting syllables read in thirty seconds [24]. In other experimental tests, different frequencies were considered, the most critical being shown to be 4 Hz, showing how accurate previous studies were. In this case, the tests involved recognition of numerical characters shown on a video: parameters, such as frequency, amplitude and direction, were made to vary. WBVs also show a negative impact on the performance of these experiments, but increasing the size of the characters and reducing the number of digits partially counteracts both the fatigue and the effect of vibration [25]. Exposure to WBV can cause increased drowsiness and loss of consciousness: beta brain waves increase their activity, and a decrease in alpha waves and heart rate is measured by electrocardiograms and electroencephalograms [10]. Medium vibration amplitude has also been shown to have a greater impact on sleepiness, like in the study performed by A. Azizan et al. [11] that considered a low amplitude value of 0.2 ms^{-2} and an average of 0.4 ms^{-2}, via a reaction test. Other relevant studies place as subject centered or sporadic attention. Sporadic, or divided, attention refers to the execution and concentration process related to multiple simultaneous activities. Centralized, or selective, attention describes the process of focusing on specific aspects [21]. The "Selective Attention Test" consists of pressing the space bar key when on a screen, on which the letters of the alphabet appear in random order, it sees the letters 'S' or 'M'. In contrast, the "Divided Attention Test" asks people not to focus on a single key, but to press "?" when 'M' appears on the right side of the screen and press "Z" when 'S' appears on the left. In both cases, when the subject is subjected to WBV, the number of correct responses decreases and the reaction time increases [26].

The effects are not, however, always negative: exposure to WBV in adults effects from attention deficit hyperactivity disorder (ADHD) allows improved quality of life and cognitive function [27]; even in those suffering from traumatic brain injury (TBI), the effects are positive [28].

In conclusion, the characteristics of vibration can be explained in 3 reactions: i) given by the physical transfer of vibration between body districts; ii) the physiological reaction manifested by changes in blood pressure, heart rate, etc.; iii) psychological reaction given by the manifestation of irritation, loss of patience, loss of attention, etc. [22].

1.4 Evaluation of vibration’s effects

Two variables are considered in evaluating the response of the human body subjected to WBV: apparent mass (AM), which is the equivalent of mechanical impedance, and transmissibility. Through these two parameters, mechanical and numerical models can then be developed [29]. AM is the ratio of force to acceleration measured at the same point, transmissibility is a dimensionless ratio calculated at different points, for example of acceleration or velocity [29]. The human body's response to vibration is nonlinearly dynamic, as its behavior changes according to certain conditions. For example, when sitting subjects are asked to contract trunk muscles, the resonance frequency increases [30]. This suggests that muscle tension plays a key role in the response to WBV. The AM matrix, therefore, is not symmetrical and the body, consequently, cannot be modeled with a concentrated parameter scheme [31]. From the contraction of buttock tissues, Y. Matsumoto deduced that as muscle tension increases, there is a decrease in the nonlinearity of apparent mass [32]. The latter result was confirmed by finite elements, which show a change in axial stiffness of the gluteal tissues at the resonance change of the AM [33]. Both mathematical models [33][34] and experimental evidence [35] have shown that bending and spine instability affect non-significantly to non-linearity and resonance. Extensive studies have been carried out on the body exposed to WBV_V (vertical), in which nonlinearity is confirmed by the decrease in resonance frequency as vibration intensity increases [36]. Sitting and standing subjects show non-linear behaviors when subjected to WBVv, specifically nonlinear features were found in resonant frequencies between 1.5 - 3 Hz [30].

1.4.1 Methods related to kinematic effects

There are three calculation methods for finding the magnitude of exposure to WBV. The first, called the 'root sum-of-square' (r.m.s.) method, is described by UNI ISO 2631-1:2014 and aims to calculate the daily vibration exposure descriptor A(8). The measured data refer to a basicentric Cartesian reference system, in which the z-axis is parallel to the spine, the y-axis perpendicular to the femoral axis, and the x-axis orthogonal to the two precursors [13].

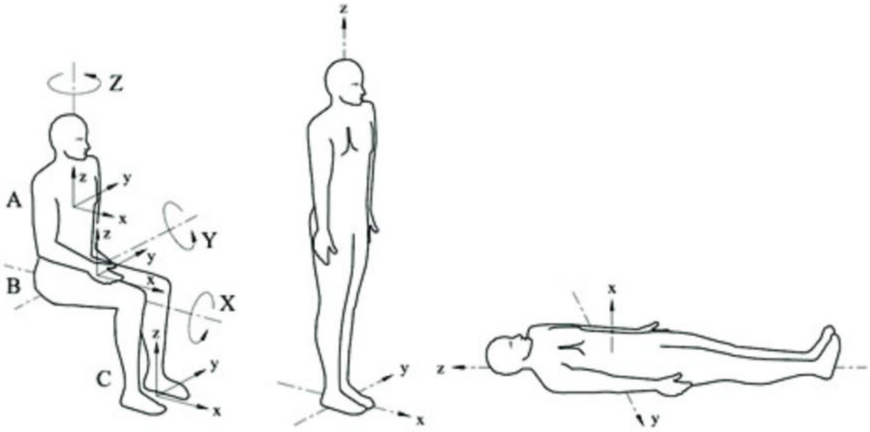


Figure 2: Reference system for seating, standing and lying subject [13]

The calculation is based on the use of frequency weighting to account for the different sensitivity of the body to vibrations of different frequencies. Specifically, the weighting will be higher for the frequencies to which the body is most sensitive; the standard defines different weighting curves for the three axes and for the three different postures. For vertical stresses the maximum is between 4-8 Hz, while for horizontal stresses it is 1-2 Hz.

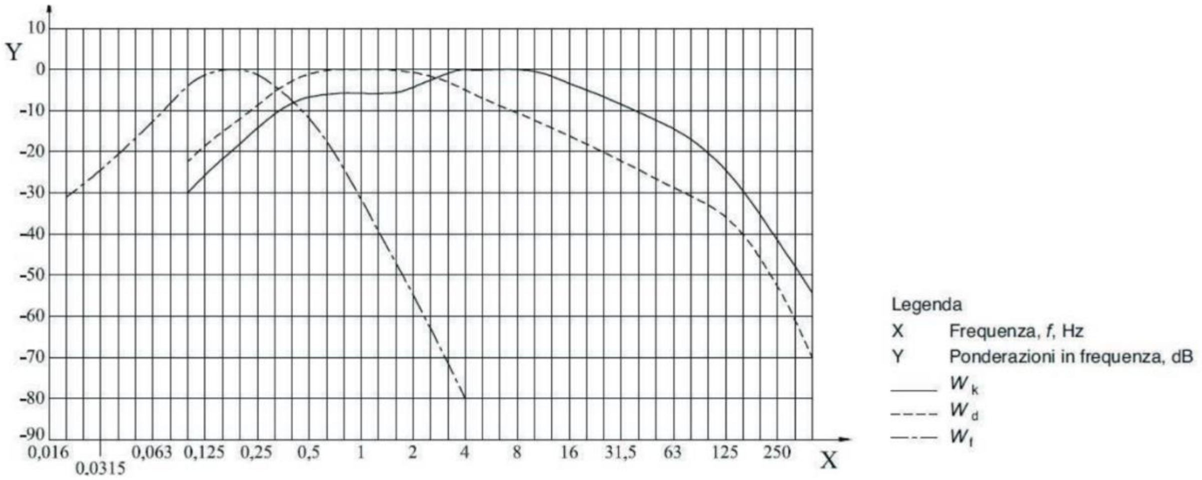


Figure 3: Weighting curves

In several studies, the reaction to vibration between seated and standing subjects was compared, with the former showing signs of discomfort under antero-posterior and lateral vibrations [37]. One motivation for this different behavior is that the standing position can counterbalance the effects of WBVs through the lower limbs joints [38], on the other hand, in the sitting position only through the movements of the back. In general, some regulatory systems are shared or activated only under particular conditions [23].

For the following cases, it is necessary to introduce the notion of equilibrium, which depends on two factors: center of mass (CoM) and center of pressure (CoP). A person, whether being in a static position or walking, to be in equilibrium must maintain CoM at CoP [40]. This represents the point at which the resulting ground reaction forces act, which changes according to the subject's bearing surface.

The studies focused on observing body behavior under three different conditions: sitting, standing and while walking. In the first case, behavior in four different positions in response to WBVv was analyzed [23].

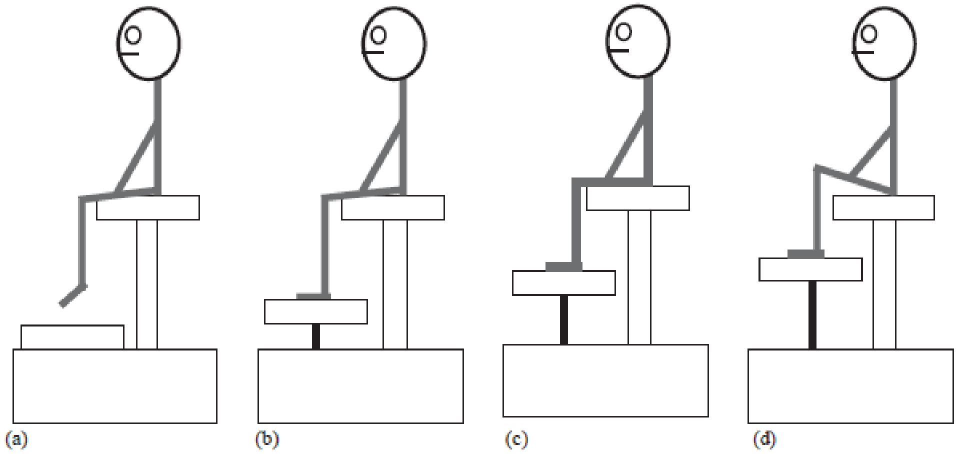


Figure 4: Diagrams of different sitting position: a) feet hanging b) maximum thigh contact c) average thigh contact d) minimum thigh contact [26]

This case study shows limited results because a uniaxial vibration was used, which does not reflect the multi-axial exposures to which workers are subjected. One study presented the differences between a uniaxial and a tri-axial case, but related to the presence of the seat backrest [39]. Only in the case of the x-axis the resonance frequency had a statistically significant difference between the presence and absence of the backrest. However, the results confirmed that the resonance of the apparent mass is about 5 Hz and that it changes as the vibration intensity vary [23].

Subjects in the standing position showed different behaviors with regard to both the difference in support (normal, bent leg, on one leg) [12], both for knee flexion (135°, 150°, 165° and 180°) [29] either by the mutual position of the feet (joined or normal) [41]. All these studies have shown that moving closer to a more stable position relative to the direction of vibration propagation reduces the transmission of vibration itself.

In cases where gait is analyzed, studies have focused on antero-posterior and mid-lateral vibrations. In both cases, the perturbations given by the vibrations change the subjects' stability and gait parameters [42]. It has been shown that, to counteract the effect of WBVs, subjects tend to modify their walking: with faster, shorter and wider strides [43]. However, the changes differ according to the direction of vibration propagation: in fact, increasing pitch length increases antero-posterior stability, but has no effect on mid-lateral stability; on the other hand, increasing amplitude has the opposite effect [44]. Adaptation to vibration is also influenced by external factors, such as visual ones. In tests in which subjects had to stare at a stationary image subjected to antero-posterior vibrations, two adaptation techniques were shown: one called 'inverted pendulum,' in which head, trunk and shank move in the same direction as the sled, and a 'hip strategy,' in which the direction of movement is opposite to the sled [45]. In tests in which the vibrations are mid-lateral, the techniques detected are: 'fixed to base,' in which the body moves synchronously with the base, and 'fixed in space,' in which there is a tendency to keep the torso fixed [46]. Use of both adaptation strategies was shown for some subjects.

1.5 Measuring instrumentation

1.5.1 Kinematics tools

The instrumentation used in the various studies mainly includes optoelectronic systems, electromagnetic systems, or IMU (Inertial Measurement Unit) inertial sensors. In some cases, video analysis systems have also been used.

Optoelectronic systems are the gold-standard evaluation method for motion analysis. They consist of reflective markers, placed in specific anatomical positions, which in relation to infrared cameras are illuminated and show their position in space, relative to a 3D reference system set [47]. The movements are recorded are completely in every direction, but these systems are usually expensive and require laboratory space and operator expertise [48].

Electromagnetic tracking systems measure three-dimensional coordinates and orientations of sensors [48]. Compared with optoelectronics, they do not have cost-related problems and do not have to be always necessarily visible like markers. On the other hand, however, they have a limited capture volume and suffer from the influence of the magnetic fields of metallic objects [49].

Inertial sensors (IMUs) enable the determination of an object's dynamics using 3D gyroscopes, angular velocity meters, 3D accelerometers, 3D magnetometers, and a barometer [50]. They are very complex tools, however, which allow more parameters to be analyzed at the same time and thus allow more in-depth studies to be carried out.

1.5.2 Cognitive tools

The evaluation of cognitive stimuli, caused by vibration, has been less developed than the kinematic aspect. In most cases, it is always a matter of measuring reaction time in performing one or more tasks subjected to different stimuli. In the case of tests to assess operators' reaction when subjected to WBV, auditory and visual stimuli were used through a computer and a monitor, the reaction time exerted through a hand command [15]. G. S. Newell and N. J. Mansfield used the 'visual motor choice reaction-time' test (VMRT) in different postures: the task requires the participant, based on the arrow displayed on a monitor, to press the relevant button on a keypad [11]. In the case of subjects with TBI (traumatic brain injury), the test involves discriminating between odd and even digits, answering in the first case with the index finger and in the second case with the middle finger of the right hand. Subjects must answer as quickly and accurately as possible [28].

One test that differs from the previous ones aims to measure short-term memory performance. The tasks require the subject to observe 2, 4, or 6 letters that are arranged in a line on a monitor for 1, 2, and 3 s, respectively. After a 1 s pause, a probe letter appears and the participant must indicate whether or not it was present among those previously displayed [10].

2. 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 motion and for cognitive data on a reaction test based on visual stimuli. The experimental trials involved six walking sessions on a treadmill subjected to 6 different vibrations conditions (0 - 2 - 4 - 6 - 8 - 10 Hz) at 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 was the 'psychomotor vigilance test' (PVT), which consisted 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.

3. Materials and methods

The testing sessions were carried out in the Human Vibration Laboratory at the Politecnico di Milano, located in the Lecco campus. The necessary equipment for conducting the experiments was installed in the laboratory. For the safety of the subjects, a support structure was created around the treadmill, and an emergency button was placed near the control station.

3.1 Experimental set-up

The set-up, as shown in Figure 5, required a space used exclusively for testing, including the infrared cameras for optoelectronic detections, the treadmill with safety stands, and the tripod supporting the diode system for PVT testing. The room had to be darkened during the tests to ensure proper detection of the reflective markers.

Figure 5: Experimental set-up in Human Vibration Laboratory

3.1.1 Treadmill

The treadmill model 'Xiaomi WalkingPad A1' is foldable and has small dimensions that allow it to take up as little space as possible. A remote control allowed its remote control.

Figure 6: Xiaomi WalkingPad A1

Following are the technical specifications:

- Motor: 746 Watts
- Speed: 0.5 to 6 Km/h
- Structure weight: 28 Kg
- Maximum capacity: 90 Kg
- Running surface: 120 x 41.5 cm
- Dimensions when open: 143 x 54.7 x 12.9 cm
- Dimensions when closed: 82.2 x 54.7 x 12.9 cm

3.1.2 Shaker

Instrument by which vibrations are generated during walking. Specifically, it generates WBV_L with variable amplitude as a function of acceleration and frequency. Connected to a motor placed on the side of the treadmill causing the entire structure on which the tests were taking place to move.

Figure 7: Keysight 33220A, 20 MHz Functional/Arbitrary Waveform Generator

Key Features [51]:

- Fully compliant to LXI Class C specification
- 20 MHz Sine and Square waveforms
- Pulse, Ramp, Triangle, Noise, and DC waveforms
- 14-bit, 50 MSa/s, 64 k-point arbitrary waveforms
- AM, FM, PM, FSK, and PWM modulation types
- Linear & logarithmic sweeps and burst operation
- 10 mVpp to 10 Vpp amplitude range
- Graph mode for visual verifica- tion of signal settings
- Connect via USB, GPIB and LAN

3.1.3 Optoelectronic system

BTS Smart DX-400 is a high-precision optoelectronic system for the biomechanical motion analysis. In the case of the tests performed, 6 infrared cameras and 32 reflective markers placed at as many relevant anatomical positions were used. The specifications of this system make it possible to fulfill the following characteristic [52]:

- Speed and accuracy: accurate marker identification, high-frequency acquisition, real-time processing
- Easy and fast calibration: takes less than 180 seconds, multivolume
- Use in critical light conditions: no loss of precision and accuracy, automatic elimination of reflections, can be installed outdoors
- Data synchronization and integration: one data station for data acquisition, processing and analysis, all kinematic, kinetic, EMG and video data acquired are synchronized
- Development tool: integration with third-party systems

The BTS SMART-DX 400 version was available in the laboratory.

Features	
Infrared Digital Cameras	Up to 16 TVCs for each datastation
Multiple workstation connection capability	Yes
Sensor resolution	1366x768 (1Mpixel)
Acquisition frequency at maximum resolution	100 fps
Maximum acquisition frequency	300 fps
Accuracy	<0.3mm on a volume 4x3x3m
Preprocessing	On cameras
Preview	Full frame
LED illuminator wavelength	850 nm
Number of markers detected simultaneously	Unlimited
Data transmission technology	Gigabit ethernet
TVC power	Directly supplied by the datastation

Lenses	Interchangeable C-mount
Case	High profile
Analog acquisition board	32-80
Passive and retro reflecting markers	0 from 3 to 20 mm
Preinstalled software	BTS SMART-Suite

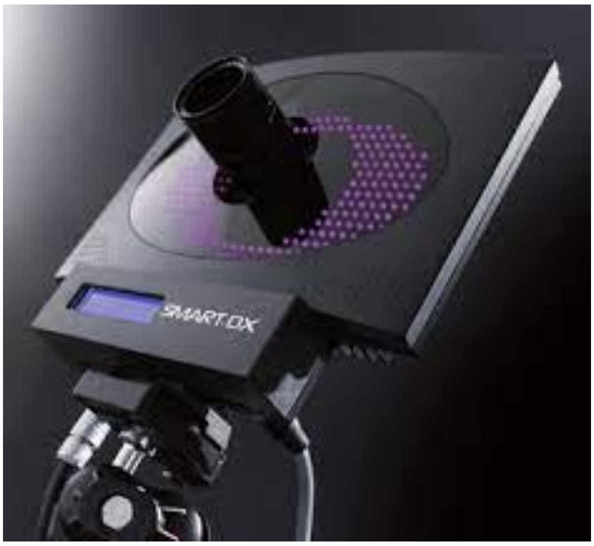


Figure 8: Infrared video camera

Figure 9: Reflective markers

3.1.4 XSENS system

The second kinematic analysis system was IMU sensors, specifically XSENS Awinda. Highly accurate, small and lightweight 3D human wireless motion tracker. In our case they were positioned on both the right and left foot, shank, thigh and one on the pelvis (pelvis). To ensure correct positioning, each sensor is attached to Velcro strap bands and for the two sensors placed in the shoes via foot pads also made of Velcro.

The trackers' compact size (47 x 30 x 13 mm) and low weight (16 g) identify it as a perfect portable device for not strictly laboratory use. Outdoors it has a communication range with the station of up to 50 m and in the laboratory of 20 m.

Each tracker consists of 3D linear accelerometers, 3D rate gyroscope, 3D magnetometers and a barometer [53]. This allows motion to be analyzed on three axes and not constrained to the field of view of cameras. The disadvantage is that these components are sensitive to the magnetic field of metallic objects.

Figure 10: Wireless human motion tracker

Each tracker is positioned according to the diagram below:

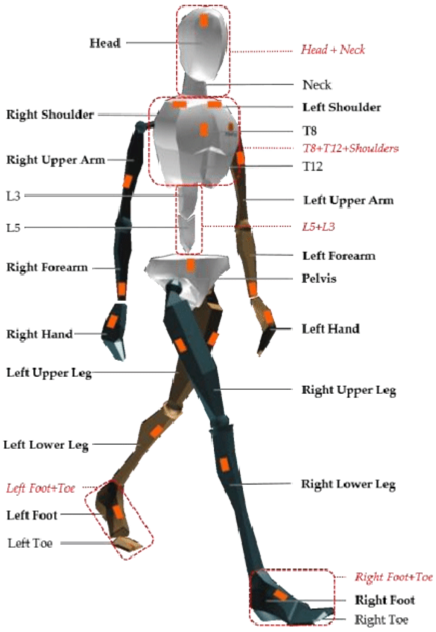


Figure 11: Map for placement of MTW [50]

In the case of this study, the positions considered are only those of the lower limbs up to the pelvis.

3.1.5 PVT

Reaction times were assessed by a psychomotor vigilance test (PVT).

Subjects had to press button in their hands during the tests as fast as possible as soon as the verse LEDs lit up. To determine the start of the test, the blue LEDs blinked three times. Each time the button is pressed the reaction time is recorded, through a Matlab code which controls the PVT test. The green LEDs light up 30 times for 90 seconds, the times between one lighting and the next are randomized.

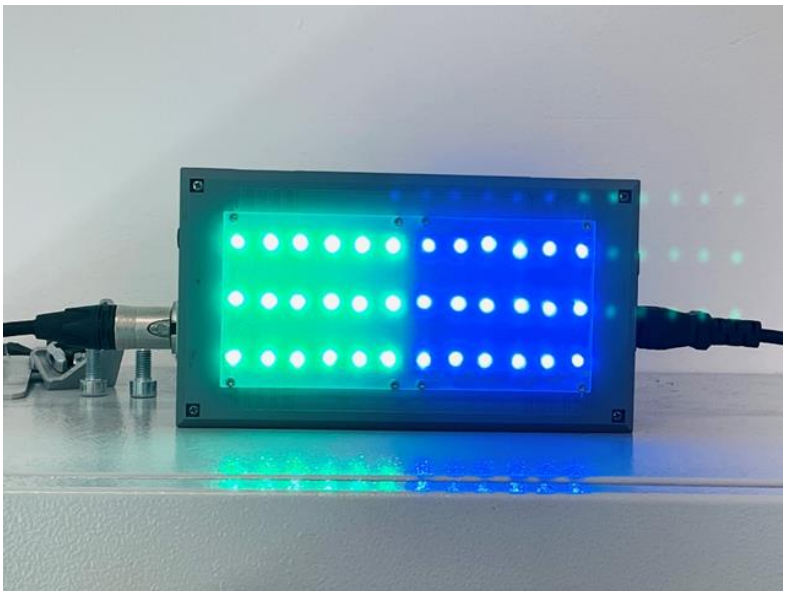


Figure 12: PVT test device, with blue and green diodes

3.2 Methods

3.2.1 Experimental protocol

The experimental protocol was approved by the institutional ethics committee. The documents, signed by the subjects, were then distributed in duplicate. It is specified how the trial durations are not intended to create fatigue, but to allow changes in kinematics and cognitive response to be observed simultaneously. Subjects must perform the 3-minute PVT test six times while walking with WBVL for a total vibration exposure of 20 minutes, a duration below the limit indicated by other studies and industry standards (ISO-2631).

The measured parameters, both with and without vibration, are:

- Cognitive reaction time [ms]
- Frequency and length of stride [1/s; m]

- Kinematic parameters, including flexion, extension, rotation, abduction and adduction of ankles, knees and hips [°]

In table 1 are made explicit all the joints considered, their respective movements and their acronyms.

Table 1: Acronyms of joints considered

Joint	**Movement**	**Acronym**
Ankle right	Flexion	AR Flex
	Inversion	AR Inv
Ankle left	Flexion	AL Flex
	Inversion	AL Inv
Knee right	Flexion	KR Flex
Knee left	Flexion	KL Flex
Hip right	Flexion	HR Flex
	Abduction	HR Abd
Hip left	Flexion	HL Flex
	Abduction	HL Abd

On the day the test is conducted, each participant is given a copy of the Informed Consent and GDPR (General data Protection Regulation) to sign. Before the experimental tests begin, the subject must be clear about the conduct and may ask questions.

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. In total he/she will therefore perform:

- 20 minutes of lateral vibration exposure with an acceleration of 1m/s^2 (3.5 minutes of vibration * 5 frequencies)
- 20 min of cognitive testing (3 minutes * 6 tests + 180 reaction times)
- 25 minutes of walking (3.5 minutes * 6 tests + turning on/off treadmill time)

The sequence of frequencies 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

If during the performance of the tests, the subject withdraws consent the test is stopped, and the related data destroyed. For those who finish all tests the data collected will be anonymized and kept for up to 2 years.

Participants must then consent to process their data for statistical and scientific purposes, including reporting in interviews and for publications.

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

3.2.2 Subjects

Participation of subjects in the experimental trials is voluntary. Males and females between the ages of 18 and 50 and who do not have any of the following conditions are 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

They are asked to indicate height, weight, date of birth and foot length for the calculation of gait parameters.

For the objective of the experiment, a total number of subjects equal to 40 was required: 20 men and 20 women. Total there were 41 participants (21 men, 20 women) volunteered for the study.

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 13.

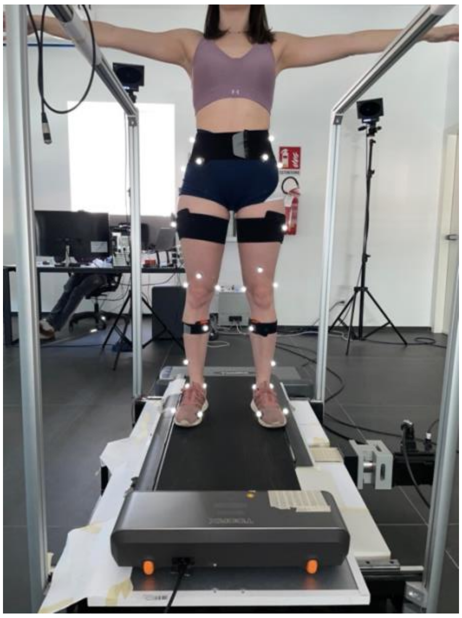


Figure 13: Calibration position with all sensors in place

3.2.3 Kinematics collection with optoelectronic system

Before testing begins, calibration of the optoelectronic system took place. Under semi-darkness conditions, a system of three Cartesian axes, with 3 reflective markers on each axis, is placed at a central location on the treadmill. Following this static acquisition, using an axis with markers, moves by varying tilt and direction to define the space to be read by the cameras during measurements. Following the dynamic acquisition, markers can be applied to the subject.

There are 32 markers to be applied and are placed on lower limbs and shoes according to the 'modified plug-in-gait marker set' protocol [54]:

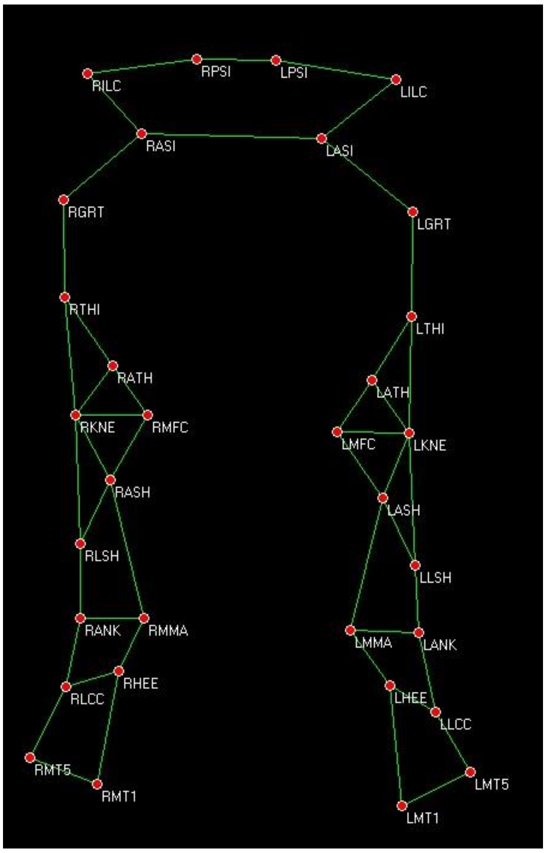


Figure 14: Marker positioning model

The anatomical points coded in Figure 14 represent the following corresponding points, excluding the first letter indicating right (R) or left (S) with respect to the sagittal plane:

- MT5 —> Fifth metatarsal
- MT1 —> First metatarsal
- LCC —> Lateral calcaneus
- HEE —> Heel (on the calcaneous at the same height above the plantar surface of the foot)
- ANK —> Ankle (on the lateral malleolus along an imaginary line that passes through the transmalleolar axis)
- MMA —> Medial Malleoli
- LSH —> Lateral shank
- ASH —> Anterior shank
- KNE —> Knee (on the flexion-extension axis of the knee)
- MFC —> Medial femoral condyle
- ATH —> Anterior thigh
- THI —> Thigh (over the lower lateral 1/3 surface of the thigh)
- GRT —> Greater trochanter
- ASI —> Anterior superior iliac
- ILC —> Iliac crests
- PSI —> Posterior superior iliac

Once the markers are applied, the subject is asked to stand upright with arms orthogonal to the body to verify that the cameras read all points correctly. Then the test can begin, recording starts 60 seconds after the subject starts walking and stops after 90 seconds.

Post-processing of the collected data is done using the SMART Tracker software, which once the model (Figure 14) is imported allows reconstruction of the gait kinematics.

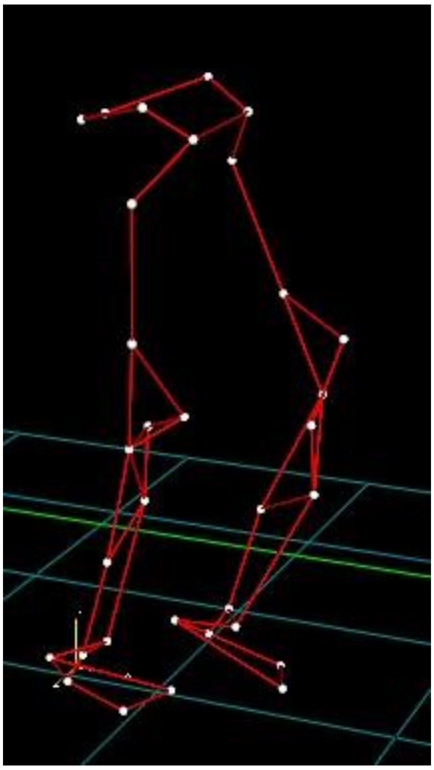


Figure 15: Lower limb reconstruction with SMART Tracker software during motion analysis

3.2.4 Kinematics collection with inertial sensors

As with optoelectronic instrumentation, IMUs also need to be calibrated before testing. Sensors are placed on the subject using Velcro bands, as in Figure 16, then asked to stand at a point in an upright position and remain motionless for a few seconds. At the signal, given by the operator, the dynamic calibration begins: the subject must walk for 15 seconds and at the end return to the starting point and position.

Figure 16: Velcro band placement and Xsens sensors [50]

After the application of sensors, the test is ready to start. Again, the recording begin after 60 seconds of walking and it ends after 90 seconds. Files recorded on Xsens as Sub#_Frequency, (i.e., Sub1_8) are uploaded to MATLAB and collected into a single structure that subdivides by frequency, by subject, and by joint. For this study, movements in the sagittal and coronal plane of the hip, knee, and ankle were considered. For each subject, the middle 60 seconds of the 90 seconds recorded during the tests are sampled, is calculated the number of steps and for each of them the degrees of rotation in the plane of the corresponding movement. 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. This method consists of eliminating all values below Q1 - 1.5*IQR (Lower Bound), where Q1 is the first quartile of the data (25% of the data lies between the minimum and this value), and all those above Q3 + 1.5*IQR (Upper Bound), where Q3 is the third quartile (75%

of the data lies between the minimum and this value). Finally, the interquartile range is defined as IQR = Q3 - Q1 [55].

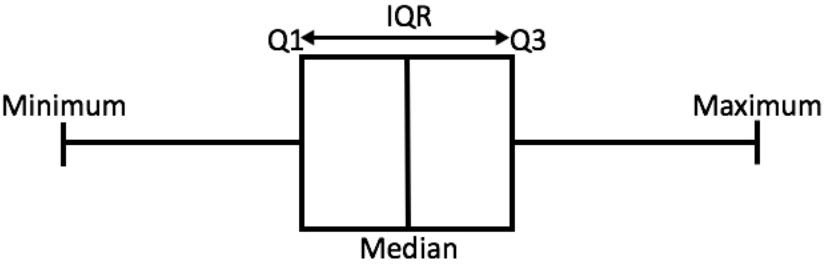


Figure 17: Boxplot depicting data distribution

Once outliers are identified, they are removed from the data sample. With those remaining, mean and standard deviation of RoMs are calculated and then statistically analyzed.

The data available for this analysis are from 31 subjects of the total 41, since there was sensor interference during testing for 10 subjects.

3.2.5 Cognitive data collection with PVT

The PVT test starts after 30 seconds of walking at the randomized frequency (or 0 Hz). When it starts, the set of blue diodes (LEDs) lights up simultaneously with the green ones three times (start signal), and after a randomized period between 2 and 9 seconds, only the set of green LEDs lights up. As soon as these light up, the subject should press the handheld button as fast as possible. 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. At the end, the LEDs turn blue again and stop blinking.

Data are organized into a MATLAB structure whose columns are only the frequencies (0, 2, 4, 6, 8, 10 Hz) and the rows are the 41 subjects who performed the tests. Again, before calculating the average reaction time of each subject for each of the six tests, the

'IQR 1.5' method was applied to eliminate outliers. Then the mean and standard deviation were calculated on which statistical analysis was done.

4. Results

Statistical analysis of the collected and post-produced data was done using MINITAB with α set to 0.05. For both PVT tests and kinematic analysis, data normality and outliers checking were first performed.

4.1 Cognitive response

The data to be analyzed from the reaction test were the average reaction times for each frequency for each subject. Kinematics and reaction time data were analyzed using mixed effect models with the participants entered as a random effect to account for model variation among individuals, and frequency level entered as fixed effects. If a significant vibration effect was found, post-hoc Bonferroni pairwise tests were performed to assess pairwise differences.

The average reaction times of each frequency are compared with the base case, the following results are obtained.

Table 2: Tests of Fixed Effects PVT

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

As is immediately noticeable none of the p-values is less than 0.05, which means the there is no correlation between reaction time and frequency.

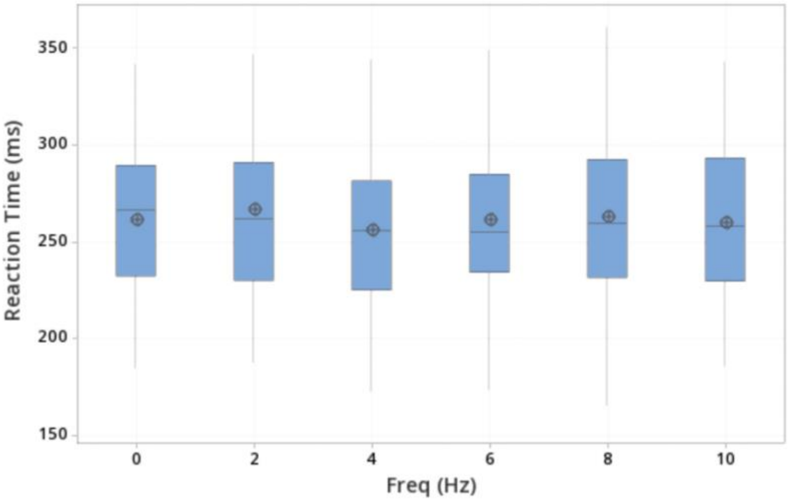


Figure 18: Boxplot of reaction time related to each frequency

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.

The variability of response for each subject to vibration was analyzed, but again no statistically significant results were obtained, as can be deduced from the graph.

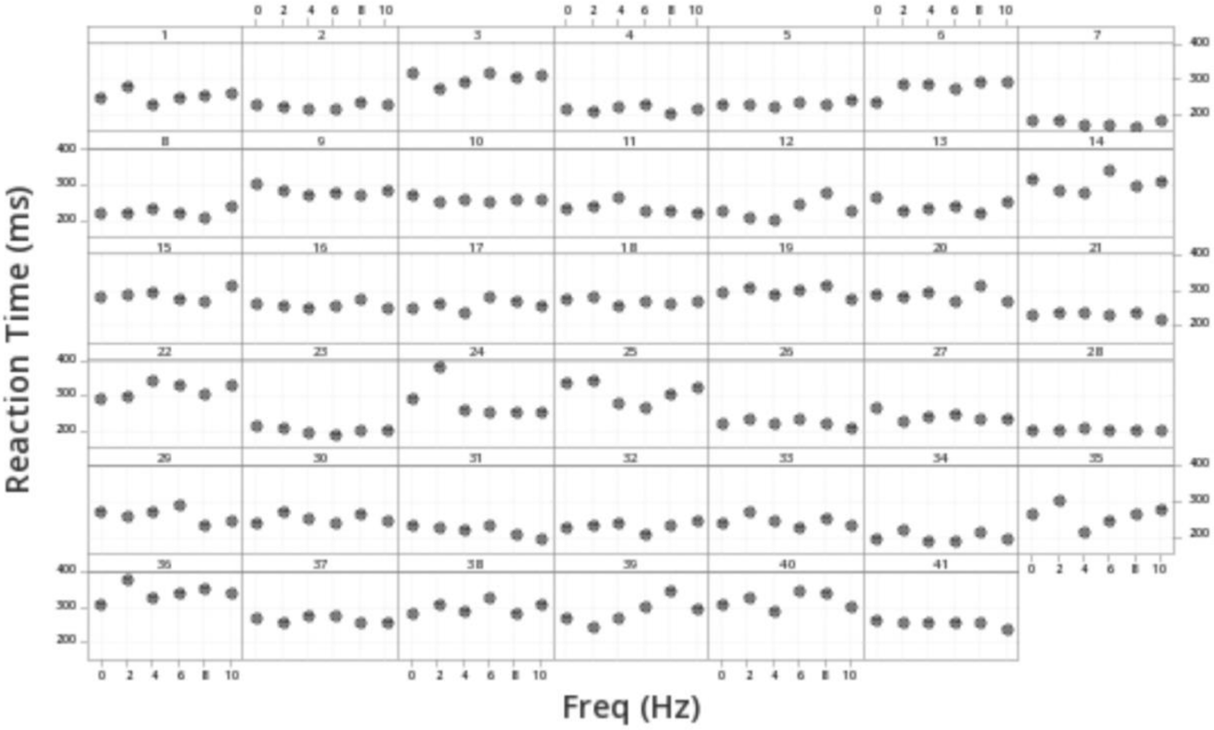


Figure 19: Boxplot to show subject variability of reaction time

4.2 Kinematic response

As for kinematic analysis, a preliminary outliers test was performed and then descriptive statistics. For each frequency the number of data studied, mean, standard deviation and boxplot main values are highlighted.

Table 3: Kinematic data descriptive statistic

Variable	FREQ	N	Mean	StDev
AR Flex	0	31	33.578	4.947
	2	31	31.740	4.782
	4	31	32.456	5.258
	6	30	32.322	4.457
	8	31	32.911	4.586
	10	31	33.842	4.823
AL Flex	0	30	32.217	4.233
	2	30	30.888	4.496
	4	31	31.286	5.179
	6	30	31.819	4.688
	8	30	31.629	3.897
	10	30	32.031	4.491
KR Flex	0	31	69.492	5.121
	2	31	67.421	4.835

	4	31	68.703	4.843
	6	31	68.32	5.87
	8	31	69.319	5.065
	10	31	69.619	5.372
KL Flex	0	31	69.933	5.452
	2	31	67.253	4.545
	4	31	68.660	5.016
	6	31	68.957	5.033
	8	31	69.125	4.679
	10	31	69.102	4.984
HR Flex	0	31	40.534	4.855
	2	31	40.136	4.126
	4	31	40.469	4.043
	6	31	39.994	4.954
	8	31	40.438	4.274
	10	30	40.816	4.370
HL Flex	0	30	40.813	4.350
	2	31	39.881	4.294
	4	31	40.152	4.290
	6	31	40.100	4.405
	8	31	40.456	4.390
	10	30	40.579	4.365

HR Abd	0	30	16.305	3.779
	2	31	14.942	3.321
	4	31	15.928	3.384
	6	30	15.677	3.391
	8	31	16.171	3.330
	10	31	16.279	3.482
HL Abd	0	31	17.051	3.120
	2	31	15.903	2.964
	4	31	16.548	3.003
	6	31	17.247	3.747
	8	31	17.101	3.230
	10	30	17.307	3.138
AR Inv	0	31	15.757	3.479
	2	31	16.193	3.909
	4	31	15.841	3.874
	6	30	15.860	3.971
	8	31	15.816	3.684
	10	31	16.132	3.656
AL Inv	0	31	16.97	6.77
	2	31	16.28	5.62
	4	31	16.60	6.05

	6	31	16.096	5.495
	8	31	16.488	5.479
	10	31	16.33	5.72
Stride freq	0	31	0.87957	0.04689
	2	31	0.91022	0.04339
	4	31	0.88602	0.04965
	6	31	0.88172	0.04642
	8	31	0.88441	0.04732
	10	31	0.87957	0.04844
Stride length	0	31	1.4250	0.0739
	2	31	1.3764	0.0667
	4	31	1.4151	0.0794
	6	31	1.4214	0.0736
	8	31	1.4172	0.0745
	10	31	1.4253	0.0773

Then 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. Obtaining the p-value less than 0.05 means that at least one pair of frequencies has a statistically significant value.

Table 4: Mixed Effects Model

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*

For each significant joint, RoMs are compared with the base case at 0 Hz using a Bonferroni pairwise correction.

The results of right and left ankle flexion, right and left knee flexion, left hip flexion, right and left hip abduction, step length and step frequency are shown in Table 3. In the three cases, right hip flexion and left and right ankle inversion, no significant differences were found and therefore the Bonferroni test was not performed.

Table 5: Bonferroni Simultaneous Tests AR Flex

Difference of FREQUENCE Levels	Difference of Means	T-Value	Adjusted P-Value
2 - 0	-1.838	-3.78	0.003
4 - 0	-1.122	-2.31	0.336
6 - 0	-0.926	-1.89	0.919
8 - 0	-0.667	-1.37	1.000
10 - 0	0.264	0.54	1.000

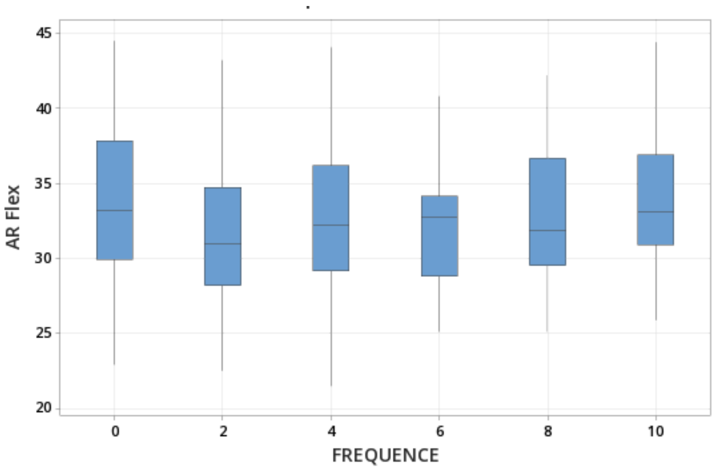


Figure 20: Boxplot of AR Flex

Table 6: Bonferroni Simultaneous Tests AL Flex

Difference of FREQUENCE Levels	Difference of Means	T-Value	Adjusted P-Value
2 - 0	-1.329	-3.22	0.024
4 - 0	-1.246	-3.03	0.044

6 - 0	-0.651	-1.57	1.000
8 - 0	-0.588	-1.42	1.000
10 - 0	-0.186	-0.45	1.000

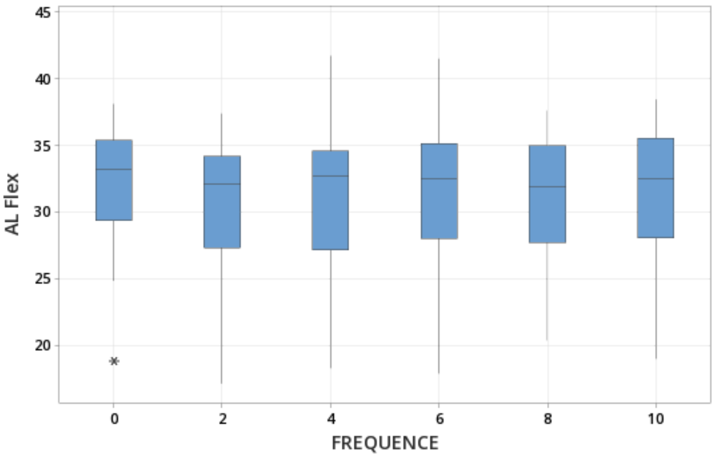


Figure 21: Boxplot of AL Flex

Table 7: Bonferroni Simultaneous Tests KR Flex

Difference of FREQUENCE Levels	**Difference of Means**	**T-Value**	**Adjusted P-Value**
2 - 0	-2.071	-4.17	0.001
4 - 0	-0.789	-1.59	1.000
6 - 0	-1.174	-2.36	0.292
8 - 0	-0.173	-0.35	1.000
10 - 0	0.127	0.25	1.000

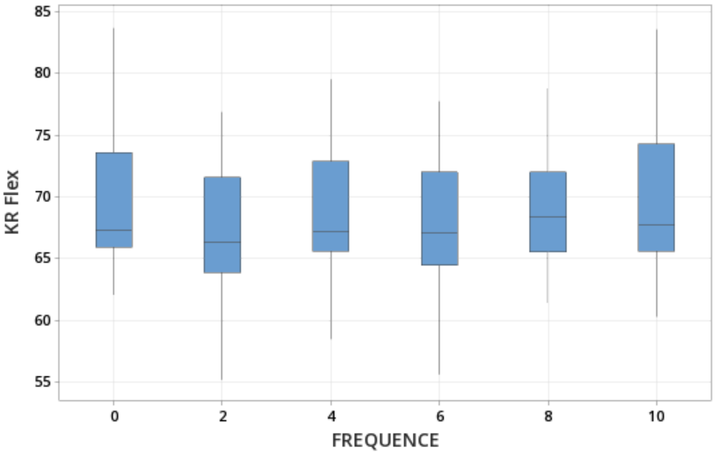


Figure 22: Boxplot of KR Flex

Table 8: Bonferroni Simultaneous Tests KL Flex

Difference of FREQUENCE Levels	**Difference of Means**	**T-Value**	**Adjusted P-Value**
2 - 0	-2.680	-5.61	0.000
4 - 0	-1.273	-2.66	0.129
6 - 0	-0.975	-2.04	0.645
8 - 0	-0.808	-1.69	1.000
10 - 0	-0.831	-1.74	1.000

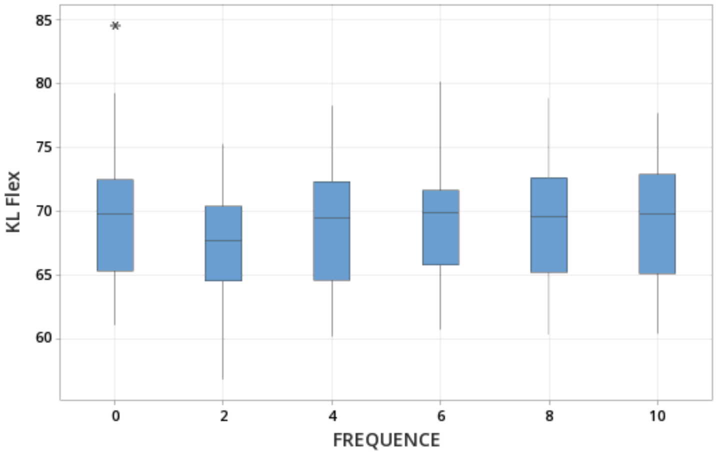


Figure 23: Boxplot of KL Flex

Table 9: Bonferroni Simultaneous Tests HL Flex

Difference of FREQUENCE Levels	**Difference of Means**	**T-Value**	**Adjusted P-Value**
2 - 0	-0.843	-3.59	0.007
4 - 0	-0.572	-2.44	0.241
6 - 0	-0.624	-2.66	0.131
8 - 0	-0.268	-1.14	1.000
10 - 0	-0.130	-0.55	1.000

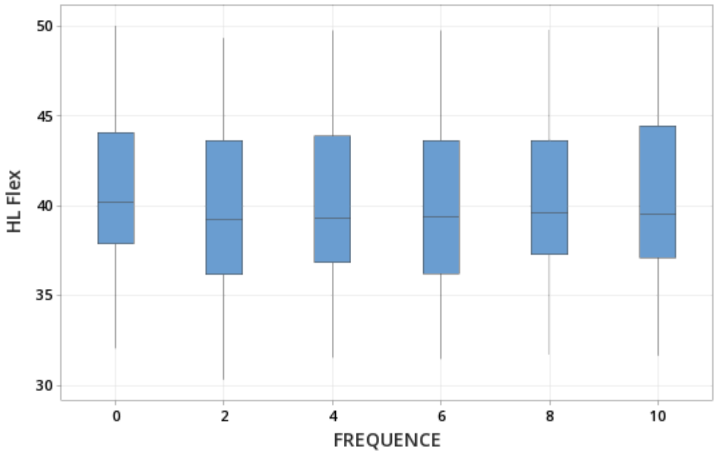


Figure 24: Boxplot of HL Flex

Table 10: Bonferroni Simultaneous Tests HR Abd

Difference of FREQUENCE Levels	**Difference of Means**	**T-Value**	**Adjusted P-Value**
2 - 0	-1.381	-6.61	0.000
4 - 0	-0.395	-1.89	0.914
6 - 0	-0.408	-1.93	0.828
8 - 0	-0.153	-0.73	1.000
10 - 0	-0.044	-0.21	1.000

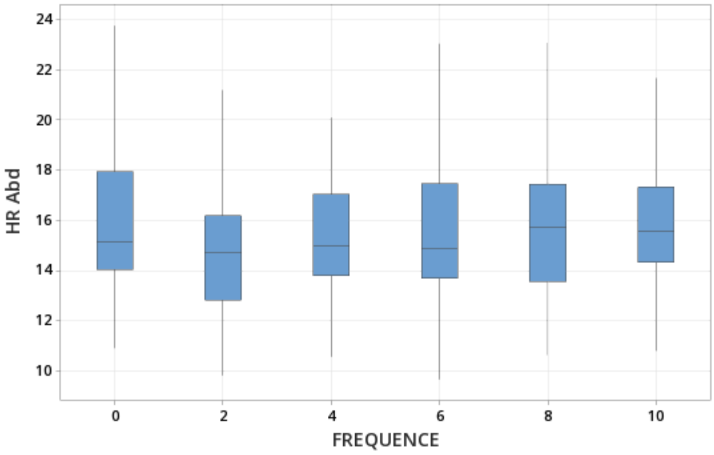


Figure 25: Boxplot of HR Abd

Table 11: Bonferroni Simultaneous Tests HL Abd

Difference of FREQUENCE Levels	**Difference of Means**	**T-Value**	**Adjusted P-Value**
2 - 0	-1.148	-3.76	0.003
4 - 0	-0.503	-1.65	0.568
6 - 0	0.196	0.64	0.987
8 - 0	0.050	0.16	1.000
10 - 0	0.092	0.30	1.000

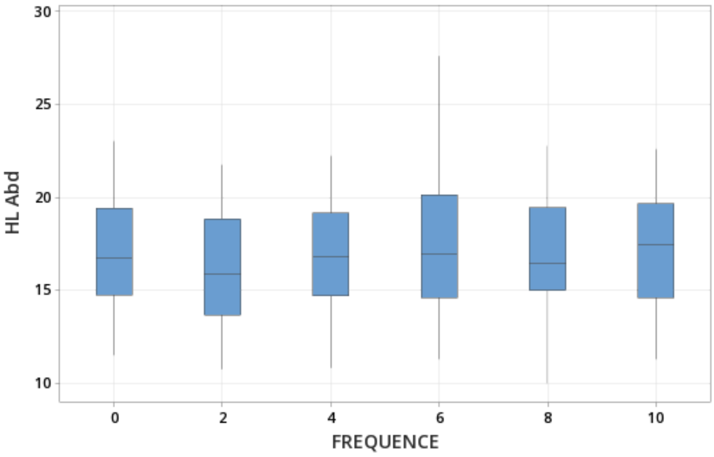


Figure 26: Boxplot of HL Abd

Table 12: Bonferroni Simultaneous Tests Stride freq

Difference of FREQUENCE Levels	**Difference of Means**	**T-Value**	**Adjusted P-Value**
2 - 0	0.03065	8.83	0.000
4 - 0	0.00645	1.86	0.977
6 - 0	0.00215	0.62	1.000
8 - 0	0.00484	1.39	1.000
10 - 0	-0.00000	-0.00	1.000

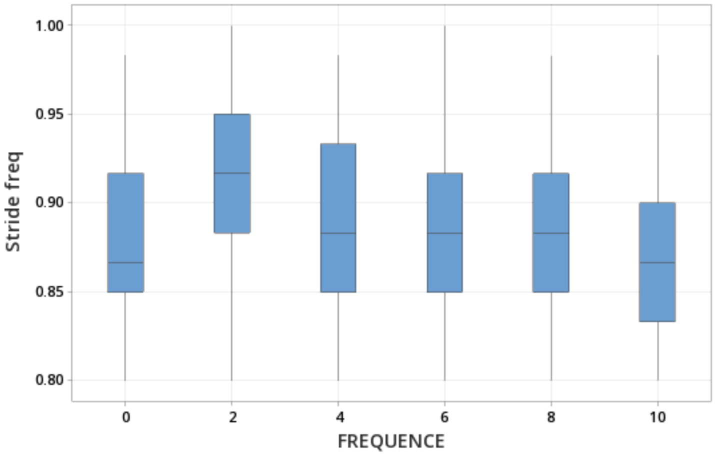


Figure 27: Boxplot of Stride freq

Table 13: Bonferroni Simultaneous Tests Stride length

Difference of FREQUENCE Levels	**Difference of Means**	**T-Value**	**Adjusted P-Value**
2 - 0	-0.04858	-8.57	0.000
4 - 0	-0.00985	-1.74	1.000
6 - 0	-0.00353	-0.62	1.000
8 - 0	-0.00773	-1.36	1.000
10 - 0	0.00031	0.05	1.000

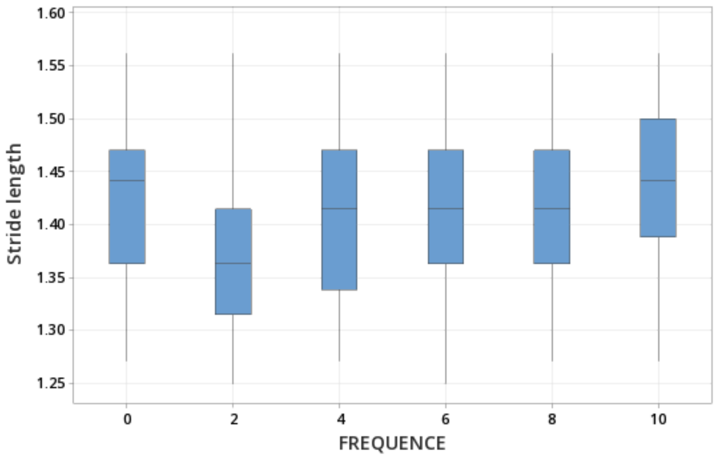


Figure 28: Boxplot of Stride length

5. Discussion

5.1 Cognitive response

As anticipated in the previous chapter, 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 0.05 threshold. Since no statistical significance was found, we did not proceed in the comparison of each frequency with the base case of 0 Hz. Result confirmed by boxplot representation, Figure 18: it can be seen that the median of the data set of each frequency does not vary significantly.

Confirmation of this result is also found in the literature, as Marelli [56] studied how WBVs acting on different axes affect reaction time, frequencies between 1.5 Hz and 12.5 Hz were considered. Using ANOVA as a statistical test, statistical significance was found only for frequencies below 2 Hz. The result of these tests is, however, in opposition to the findings of M.J. Griffin et al. [24], who find the frequency of 4 Hz particularly significant on increasing reaction time. The reasons may be related to the different parameters considered as well as the different posture the subjects are in.

Variability for individual subjects was also investigated, but it does not allow determining an objective rule on how reaction time is affected.

5.2 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 baseline (no vibrations) condition. 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. What is of interest, however, is whether the subject changes the way he or she walks when subjected to a particular frequency. To determine this, we cannot rely solely on statistical significance, but must quantitatively assess whether the difference leads to a significant change. Descriptive statistics allow us to determine when a change in movement is considered significant; this happen when the difference in RoM between the frequency at 2 Hz and 0 Hz is greater than |1|.

The significance of the results is in agreement with the study by N. Shibata [37], who considering a wider range of vibration frequencies established how WBVLs are a source of discomfort. The change in pitch regularity is a consequence of this. That the frequency of 2 Hz was of particular interest finds confirmation in the study done by T. Fairley et al. [30], in fact the resonance frequency, decreases as the magnitude of vibration increases.

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 [43]: an increase in stride length, so even an increase in hip flexion has no effect on medial-lateral stability, instead an increase in amplitude (hip abduction) increases its stability [44].

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. In the same way, Directive 89/391/EEC also 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. For example, during whole-body lateral vibrations, the frequency of 2 Hz and 18 mm amplitude should be adjusted and studied more thoroughly.

6. Conclusion and future development

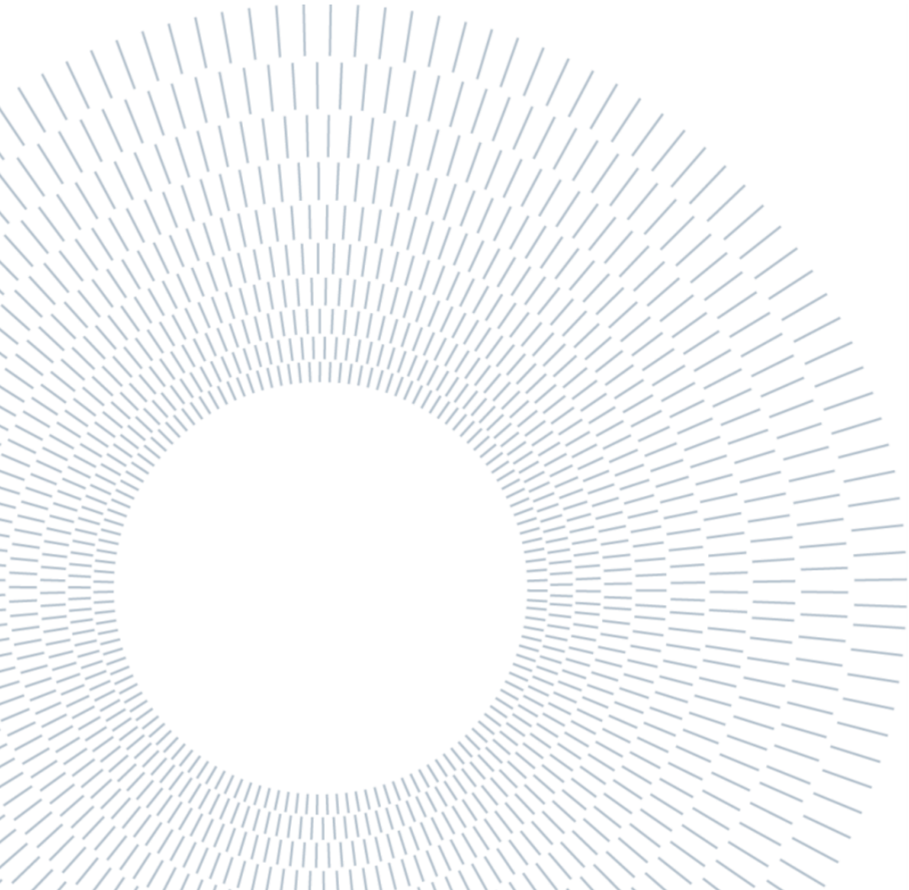
Whole-body vibrations are perturbations that can propagate through the human body, and if exposure remained for a prolonged time, they could cause physical and cognitive damage. To avoid health repercussions, guidelines have been created, suggesting methods to counteract adverse effects, standards, indicating how to evaluate them, and studies discovering new implications both beneficial and harmful. Of particular interest are the consequences they have kinematically and on cognitive response.

To assess movement, the analysis focused on changes in rotation angles in the sagittal and coronal plane: hip, knee and ankle flexion, hip abduction, and ankle inversion. In addition, changes on stride frequency and stride length are analyzed. Cognitive assessment was performed by a reaction test, Psychomotor vigilance test PVT. For the purpose of this thesis, only the results obtained with the IMU sensors and the PVT were considered.

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. Other studies show that there is statistical dependance when changing parameters of interest or vibration characteristics.

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 changes 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.

To deepen and develop the research carried out in this thesis, keeping the same experimental set-up, it is necessary to investigate different frequencies, not in the range of 2 - 10 Hz, to look for significance in the cognitive response. A further development is to compare the results obtained with the IMU system with the gold-standard, optoelectronic system, to further validating the results obtained.



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A. Appendix A

XSENS extraction data code:

The main body of the code defines the walking conditions (the frequencies), the variables being analyzed (the joints), and the movement to be studied. In addition, the first and last 15 seconds that were recorded are "cut off," so that there are 60 seconds of data for all tests. After applying the functions below, the "Subjects" structure is created containing the joint angles for each step taken by each subject.

```
Files = dir('**/*.mat');
%% Create Variables Matrices %%
global frequencies
frequencies=["zero", "two", "four", "six", "eight", "ten"]; %Conditions
during walk
global variable_names
variable_names=["HR","KR","AR","HL","KL","AL"]; % Variables R/L Hip, Knee,
Ankle, Foot Contact
global variable_numbers
variable_numbers=[15,16,17,19,20,21]; %Field number w/i data structure to
call Var
global variable_columns
variable_columns=[1,1,1,1,1,1]; % Column of Var for 1:Ab/Aduction
2:Rotation 3:Flexion
parts_of_foot=["LH" "RH"];%,"LT","RH","RT"]; %Foot contacts for R/L heel
and toe
n_files=length(Files);
for i_var=1:length(variable_names)
    Variables(i_var,1).name=variable_names(i_var);
    Variables(i_var,1).number=variable_numbers(i_var);
    Variables(i_var,1).column=variable_columns(i_var);
end
%% Find Heel Strikes // Cut all Variables by Strides // Store in Stucture
cd /Users/*****/Desktop/XSENS/xsens-data
path = ('/Users/******/Desktop/XSENS/xsens-data');
row=0;
n_stride=0;
global shortest
```

```
shortest=500;
for i_file=[1:42,49:n_files]%1:n_files
    j=0;
    file=getfield(Files,{i_file},'name');
    sub_freq=split(file,'_');
    freq=split(sub_freq(2),'-001.mat');
    freq=string(freq(1));
    if freq=='0'
        freq='zero';
    elseif freq=='2'
        freq='two';
    elseif freq=='4'
        freq='four';
    elseif freq=='6'
        freq='six';
    elseif freq=='8'
        freq='eight';
    elseif freq=='10'
        freq='ten';
    end
    add=mod(i_file,6);
    if add==1
        row=row+1;
    end
    subj=string(sub_freq(1));
    file=strcat(path,'/',file);
    load(file);
    n_samp=size(tree.footContact(1).footContacts,1);
    diff=n_samp-6000; %6,000 frames in 60 secondi
    start=floor(diff/2);
    finish=start+5999;
    LH=tree.footContact(1).footContacts(start:finish);
    RH=tree.footContact(3).footContacts(start:finish);
    cut_indxs_L=heel_strikes2(LH); % Identifies consecutive heel strike
indices for later separating strides
    cut_indxs_L=Fill_Gaps_3_100Hz(cut_indxs_L); %Combines any strides which
were cut by the 'heel_strikes2' function
    cut_indxs_R=heel_strikes2(RH); % Identifies consecutive heel strike
indices for later separating strides
    cut_indxs_R=Fill_Gaps_3_100Hz(cut_indxs_R); %Combines any strides which
were cut by the 'heel_strikes2' function
    for i_var=1:length(variable_names)
        v_name=Variables(i_var).name;
        TF=contains(v_name,'L');
        if TF==1
            cut_indxs=cut_indxs_L;
            side=1;
        else
            cut_indxs=cut_indxs_R;
            side=2;
        end
        v_num=Variables(i_var).number;
        v_col=Variables(i_var).column;
        t_var=tree.jointData(v_num).jointAngle(start:finish,v_col);
        Subjects(row,1).Subject=subj;
        Norm_Subs(row,1).Subject=subj;
```

```
            for i_strides=1:length(cut_indxs)-1
                heel1=cut_indxs(i_strides);
                heel2=cut_indxs(i_strides+1);
                stride_data=t_var(heel1:heel2);
                new_short=length(stride_data);
                if new_short<shortest
                    shortest=new_short;
                    num_file=i_file;
                end
                sn=i_strides;
                stride=strcat('Stride',num2str(sn));
                Strides(sn,1).Stride=stride;
                Strides(sn,1).(v_name)=stride_data;
                n_stride=i_strides;
            end
        end
        j=j+n_stride;
        Subjects(row,1).(freq)=Strides;
        clear Strides
    end
```

heel_strikes2 function: by identifying the point of contact of the heel divide the angles for each stride

```
function [indxs]=heel_strikes2(contact_data)
for i=1:length(contact_data)-1
    change(i,1)=contact_data(i)-contact_data(i+1);
end
indx_chng=find(change)+1;
if contact_data(1)==1
    indx_chng(1)=[];
end
j=1;
for i=1:floor(length(indx_chng)/2)-1
    a=indx_chng(j);
    j=2*i+1;
    b=indx_chng(j);
    indx_chng2(i,1)=a;
    indx_chng2(i,2)=b;
    indx_chng2(i,3)=b-a;
end
indxs=indx_chng2;
clear change
clear indx_chng
clear diff
end
```

Fill_Gaps_3_100Hz function: this function identifies if some strides are not counted

```
%% Control for Fixing Holes %%
function [data_new,extra]=Fill_Gaps(data)
n=size(data,1)-1;
thresh_low=63; % sets stride length theshold to 150 data points ~0.625
data_down=data(:,1); % the previous threshold was set as a measure of SD
```

```
data_up=data(:,2); % However this does not work when there are multiple
data_diff=data(:,3); % Strides which were split in half becasue it leads
j=-1; % to a high SD and then either short strides are let through if the
k=0; % SD multiplier is too high or multiple stride are combined if the
for i=1:n % SD multipplier is too low
    diff=data_diff(i); % instead a manual threshold was set which can also
    if diff<thresh_low % be updated should it be necessary
        data_down(i-j)=[];
        data_up(i-k)=[];
        j=j+1;
        k=k+1;
    end
end
extra=k;
data_new=[data_down,data_up];
n=size(data_new,1);
data_new(:,3)=data_new(:,2)-data_new(:,1); %stride time
end
```

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