Development of a Wearable Sensors System to Monitor Foot-Transmitted Vibration

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Abstract. Exposure to mechanical vibration may lead to harmful effects on the human body if it does not occur within a controlled environment. ISO 2631-1 regulates how to measure the vibration exposure and provides safety limits. According to this standard, the acceleration signals should be measured at the interface between the vibrating surface and the human body for a time interval long enough to represent a whole working shift. This is impossible to achieve in the case of foot-transmitted vibration, as standard equipment cannot fit between the foot and the floor. For this reason, a new system of sensors has been developed to be small enough to fit inside a regular foot insole. This system is powered through batteries and transmits the data to a cellphone through the Bluetooth connection, thus enabling a precise and continuous measurement. After production, the system has been validated by comparing the vibration exposure measured with the insoles to the vibration measured by standard piezo-electric accelerometers. The validation process took place both in laboratory controlled conditions and in real, outdoor conditions. The experimental results show a root-mean-squared error in the evaluation of vibration exposure lower than 0.1 m/s^2, thus proving the potential of the proposed system.

Keywords: Wearable sensors · Mems · Foot-transmitted vibration · Vibration exposure

1 Introduction

The harmful effects of occupational exposure to whole-body mechanical vibration are well documented in the scientific literature [1]. These effects may be acute, like discomfort, low back pain [2], nausea, dizziness, temporary loss of sensitivity [3]; or even

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persistent, leading to sciatica [4] or vibration-induced white foot syndrome [5]. Monitoring vibration, therefore, is crucial to the well-being of workers and, in general, of all the people regularly exposed to vibration. ISO 2631-1 [6] was created to regulate how to measure the acceleration and compute the vibration exposure of workers. It imposes that the acceleration must be measured at the interface between the vibrating surface and the part of the human body in contact with it. The regulation distinguishes three main contexts in which the mechanical stimulus can enter in the human body: while sitting, while laying and while standing. Seats and beds are generally thick enough to contain regular accelerometers and data acquisition systems. Measuring acceleration at the interface between the feet and floor, however, is challenging for two main reasons. The first is the small space available, while the second is the need for a wireless system, as wired shoes may prove to be cumbersome to wear and will obstruct natural movement. Given these problems, this paper presents a new measurement system, small enough to be placed inside a regular pair of shoes insoles, able to evaluate the vibration exposure and wirelessly transmit the data acquired to a cell phone.

The acceleration between the feet and the supporting surface as well as the overall environmental conditions of the feet can be directly measured through a two-sensor system placed inside the insoles of the shoes, in dedicated slots; one below the heel and one in correspondence of the forefoot. The sensors used to compose each system are tri-axis MEMS accelerometer ST LIS3DH [7], manufactured by STMicroelectronic (Plan-les-Ouates, Chemin du Champ-des-Filles 39, CH), and the force sensitive resistor 402 FSR, manufactured by Interlink Electronics (31248 Oak Crest, Westlake Village, CA United States). The acceleration range for the accelerometers is to ±4 g, and the acceleration data are acquired with a frequency of 200 Hz. The pressure data are read with a frequency of 10 Hz. The change of resistance of the FSR is evaluated through a voltage divider configuration, as was done by Spinsante et al. [8]. Given the documented uncertainty of such sensors [8, 9], the pressure data are compared to an arbitrary threshold of 1.5 V; below which it is supposed that the load of a person is being applied. The digital temperature sensor STLM75, produced by STMicroelectronic is also included in the system, as low temperature can be a determining factor in the onset of vibration-induced foot pathologies [10]. The system described is shown in Fig. 1, and has nominal dimensions of $30 \times 30 \times 5$ mm.

The vibration exposure is then automatically computed according to ISO 2631-1 by the acquisition system itself, based on the acceleration signals acquired by all four accelerometers available inside the insoles. Each second, the updated values of vibration exposure, together with the pressure and temperature data are then sent to a smartphone through the Bluetooth® low energy protocol by the module SPBTLE-1S, produced by STMicroelectronic, which also includes the CPU for controlling the system. The data can also be stored on board, through the flash memory MX25R1635FZUIL0, produced by Macronix (Hsinchu, Taiwan, R.O.C.). The whole system is powered by a CR2032 battery, which can be recharged through the wireless recharge coil AWCCA-36R36H08-C51-B, produced by Abracon LLC (Spicewood, TX, USA). Two data acquisition modules are inserted inside one insole, as shown in Fig. 2. This allows the measurement of the vibration transmitted to both fore and rear foot, as these two components may play a different role in the transmission of vibration through to foot to the rest of the body [11].

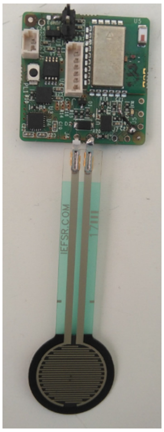

Fig. 1. Photograph showing the sensors system

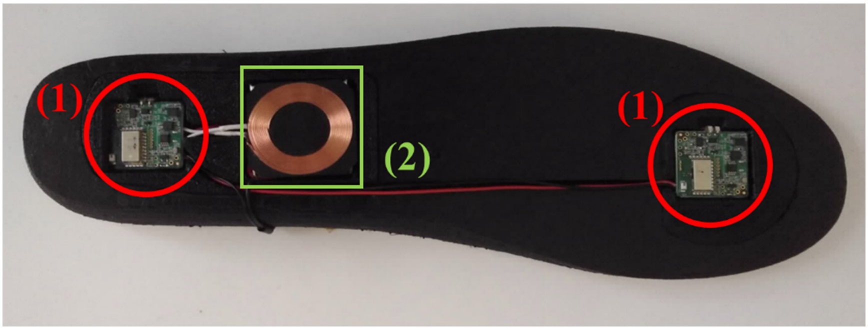

Fig. 2. Photograph of the different components of the data acquisition and transmission system inside the insole. (1): Data acquisition and transmission systems (2) Wireless recharge coil and battery

2 Method

2.1 Participants Information

Experiments were performed with 5, healthy (no injuries or ailments within the previous 6 months), male subjects (age 27 ± 3 years, height 178 ± 5 cm, mass 73 ± 14 kg; mean ± SD). Three subjects performed the bicycle tests, two subjects performed the ski tests. One of the subjects which participated in both of the outdoor tests also performed the indoor laboratory tests. All subjects were provided and signed informed consents prior to the experiments.

2.2 Laboratory Testing

Five pairs of sensorized insoles have been prototyped for the testing and validation phase. Two different tests were performed in laboratory conditions. The first was aimed at evaluating the metrological properties of the system, while the second was aimed at evaluating the effect that the soles of the shoes may have on the measurements. First, the five different prototypes have been placed, one at a time, on a vibrating platform able to move along the three mutually perpendicular spatial axes, with a person standing on them, as shown in Fig. 3. Then, one pair was extracted randomly and placed inside three different shoes: a pair of mountain bike shoes, a pair of working boots with rubber soles and a pair of working boots with polyurethane soles. A person wore the shoes and stood on the same platform used for the tests previously explained. For each prototype and shoe kind, four different signals have been used. For each spatial axis, a white noise signal has been imposed. The nominal RMS amplitude was 0.5 m/s^2. The frequency components were between 0.5 Hz and 20 Hz, and the duration was 60 s. Then, a pseudo-random signal was imposed to all three axes simultaneously. The nominal RMS amplitude was 0.5 m/s^2, the frequency components were between 0.5 Hz and 50 Hz, and the duration was 120 s. The order of execution of the tests has been randomized. For all tests, the reference acceleration signal was measured through the triaxial accelerometer 356A22 manufactured by PCB Piezotronics (Depew, NY, USA), placed in the middle of the vibrating platform. The data acquisition board National Instruments 9234 (Austin, TX, USA) was used to sample the data with a rate of 2048 Hz. A parallel manipulator specifically made for this purpose actuated the vibrating platform [12].

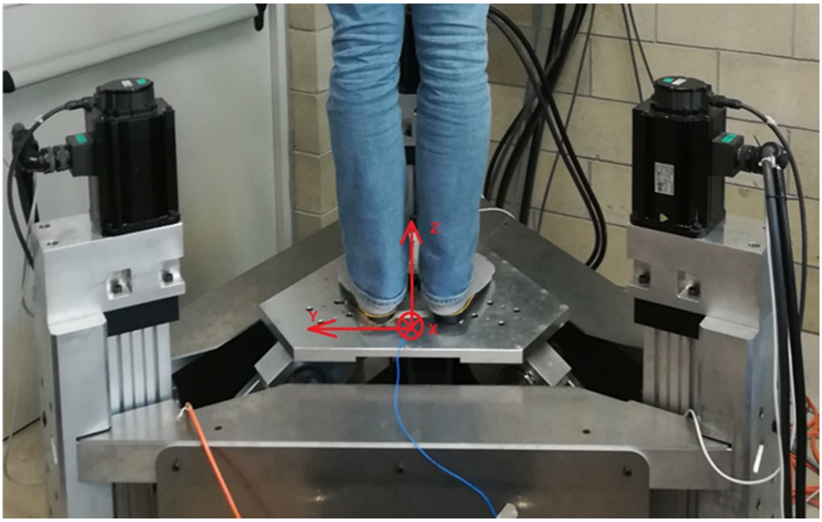

Fig. 3. Picture of a person standing on the vibrating platform during the tests of the prototyped insoles.

2.3 Outdoor Testing

Two different tests were performed in outdoor conditions and were aimed at evaluating the performances and the reliability of the system in an uncontrolled environment.

Mountain biking was used as the case study for the first test. Three different subjects were asked to repeat a predetermined route inside the university campus five times. The subjects were instructed on the route to follow and to not use the saddle of the bicycle to increase the dose of vibration absorbed through the feet. The same instruments used to acquire the reference signal in the tests executed inside were also used for this tests. In this case, the reference accelerometer was placed on the right pedal of the bike.

Skiing was selected as the second testing condition for the sensors system. Two different subjects took part in this testing activity, and each of them sported a different setup. The instruments used to compose the first setup were the same used for the indoor testing and for the tests on the mountain bike. The triaxial accelerometer was placed close to the right heel, on the ski. The second setup was composed of four single-axis accelerometers 5508 B made by BRÜEL & KJÆR SOUND & VIBRATION MEASUREMENT (Nærum, Denmark). These accelerometers were placed on the skis, close to the heels and to the tips of the feet, to be as close as possible to the sensors placed onside the insoles. Being single-axis, the reference accelerometers were mounted to measure the vertical vibrations, which were found to be the most relevant during the skiing activity [13]. No instructions were given to the subjects about the routes to follow, except that they each had to cover 9 different paths. The test took place on the ski area of Piani di Bobbio (LC, Italy).

2.4 Data Analysis

The acceleration signals measured by the reference accelerometers were used to compute the vibration exposure as regulated by ISO 2631-1. The frequency weighting curve "Wk" was applied to the signals measured along the vertical axis, while the frequency weighting curve "Wd" was applied to the signals measured along the two horizontal axes. The vibration exposure was then computed for each direction and measurement point through the running RMS method. Finally, the overall vibration total value was computed as the root-sum-of-squares of the vibration exposures evaluated for each direction and measurement point. The values of vibration exposure measured by both systems were compared by computing their absolute and percentage differences. Since the pressure distribution within the boot or shoe could not be controlled during dynamic tests, the RMS values of all four insole sensors were compared to determine outliers. Tests were eliminated if one of two situations occurred; one, the reference sensor registered a value which was an outlier compared to the other trials of the same subject, or two, the RMS of the four insole sensors resulted in a value which was an outlier compared to the other trials of the same subject.

3 Results

3.1 Laboratory Testing

Results from the laboratory testing without shoes (Table 1) and with shoes (Table 2) are presented as the mean measurement of the four sensors across all five tests. Results show that the sensorized insoles performed much better being placed inside of shoes than they did being stood upon without shoes. While the percent error is greater than 30% in some instances, particularly without shoes, it should be noted that the absolute difference is still less than 0.1 m/s^2 in both cases.

Table 1. Sensorized insole testing without shoes

Direction of vibration	Mean vibration of 4 insole sensors (m/s^2)	Vibration of reference accelerometer (m/s^2)	Absolute difference	Percent error
X Vibration	0.241	0.176	0.065	36.669
Y Vibration	0.223	0.170	0.053	30.825
Z Vibration	0.352	0.376	0.024	6.416
3D Vibration	0.546	0.490	0.056	11.482

Table 2. Sensorized insole testing with shoes

Direction of vibration	Mean vibration of 4 insole sensors (m/s^2)	Vibration of reference accelerometer (m/s^2)	Absolute difference	Percent error
X Vibration	0.205	0.180	0.025	13.836
Y Vibration	0.197	0.180	0.017	9.409
Z Vibration	0.350	0.380	0.030	7.882
3D Vibration	0.538	0.500	0.038	7.565

3.2 Outdoor Testing

Results from the two outdoor tests, riding a bicycle (Table 3) and skiing (Table 4) are presented below, including the tests which were eliminated due to outliers. The means are taken of each column (R Toe, R Heel, L Toe, L Heel) of each subject and the absolute difference as well as the percent error is taken as the difference between the RMS and reference sensor of each row (trial). While the percentage errors among singular trials can occasionally exceed 20% during bicycling, the mean percentage error of all trials for each subject was less than 5% for two of them. The ski tests unfortunately resulted in 7 out of 18 tests being eliminated. Similar to the bicycle tests however, when taking the mean of the valid tests, one of the subjects had a low percent error (just under 6%).

Table 3. Outdoor bicycle tests

Subject.Trial	R Toe	R Heel	L Toe	L Heel	RMS	Ref.	% error
S1.T1	0.216	0.426	0.295	0.214	0.300	2.578	88.351
S1.T2	0.648	0.655	3.894	1.977	2.232	2.480	10.032
S1.T3	3.842	2.908	2.862	2.385	3.045	2.734	11.405
S1.T4	3.422	2.641	3.241	2.043	2.888	2.564	12.622
S1.T5	3.921	2.753	3.988	1.930	3.263	2.688	21.404
RMS S1	2.909	2.174	3.158	1.873	2.582	2.610	1.090
S2.T1	2.612	2.348	2.819	2.399	2.551	3.870	34.079
S2.T2	1.127	3.155	1.065	0.322	1.765	24.567	92.815
S2.T3	4.436	3.267	4.850	1.378	3.734	3.492	6.923
S2.T4	4.712	3.489	5.094	3.112	4.184	3.326	25.782
S2.T5	4.455	3.846	5.395	3.148	4.291	3.792	13.159
RMS S2	3.737	3.259	4.187	2.339	3.754	3.627	3.502
S3.T1	4.731	3.294	0.000	1.398	3.425	3.401	0.707
S3.T2	4.224	3.168	3.876	2.958	3.593	3.562	0.888
S3.T3	4.594	2.878	4.140	2.790	3.685	2.980	23.644
S3.T4	5.735	3.725	5.305	3.689	4.704	3.926	19.826
S3.T5	4.762	3.598	5.053	3.160	4.217	3.634	16.048
RMS S3	4.835	3.346	4.143	2.901	3.953	3.514	12.486

Table 4. Outdoor ski tests

Subject.Trial	R Toe	R Heel	L Toe	L Heel	Mean	Ref.	% error
S1.T1	2.657	3.473	2.744	0.948	2.624	2.643	0.699
S1.T2	5.234	5.560	5.836	3.080	5.046	6.716	24.866
S1.T3	5.632	5.173	4.173	5.952	5.275	5.688	7.254
S1.T4	5.003	3.720	0.874	4.155	3.771	0.928	306.343
S1.T5	2.014	2.603	0.102	2.345	2.021	6.317	68.006
S1.T6	0.108	1.702	1.459	1.772	1.430	1.780	19.655
S1.T7	4.156	0.640	0.000	4.337	3.488	3.529	1.186
S1.T8	2.323	2.833	0.000	2.766	2.650	0.698	279.460
S1.T9	2.364	3.038	2.284	2.794	2.638	4.169	36.716
RMS S1	1.810	1.787	1.393	1.769	1.793	1.899	5.584
S2.T1	3.305	2.934	3.324	4.450	3.549	2.896	22.526
S2.T2	-	-	-	-	-	5.909	-
S2.T3	-	-	-	-	-	7.908	-
S2.T4	-	-	-	-	-	1.007	-
S2.T5	-	-	-	-	-	1.421	-
S2.T6	1.971	1.483	2.092	1.466	1.776	1.876	24.969
S2.T7	2.662	2.143	3.056	2.306	2.566	3.950	36.783
S2.T8	3.370	3.097	3.674	3.160	3.333	2.676	15.625
S2.T9	2.243	2.099	2.460	2.401	2.305	2.643	13.860
RMS S2	1.646	1.533	1.709	1.660	1.645	2.016	18.420

4 Discussion and Conclusion

A sensor system has been developed specifically to continuously measure the vibration exposure of subjects exposed to foot-transmitted vibration. The system is fully integrated inside a pair of regular shoe insoles and can transmit the acquired data wirelessly to a smartphone. The system has been validated both in controlled conditions and during realistic use, by comparing the vibration exposure measured by it with the one evaluated by reference piezoelectric accelerometers. The results show that in lab conditions, the insoles function best ($\leq$14% error) while inserted into a pair of shoes as designed rather than outside of the shoes. In outdoor tests, it was found that, while a single test may have an error over- or underestimation of over 30% at times, when averaging the measurements of as few as just 5 tests, the percentage error can drop to as low as nearly 1% during cycling in controlled conditions and 5.6% in uncontrolled skiing tests with just seven trials. The main weakness of the system is related to the wireless data transmission system through the Bluetooth protocol, which is not always reliable, causing a loss of information. This issue may be solved by increasing the time interval after which the new data are sent to the cellphone, thus decreasing the data transmission rate. Another improvement to be made is the implementation of smart algorithm to recognize and neglect corrupted or non-meaningful data set. This algorithm may benefit from the wide variety of measured physical quantities, as it was suggested by the preliminary results obtained from the tests done on the mountain bike (if considering only the sensor with high pressure, i.e. in contact, the error decreases). As the research on foot-transmitted vibration progress, monitoring both forefoot and heel may be a key advantage, in preventing vibration-related diseases and disorders. In particular, a system such as this could be further developed and tested in a greater number of contexts with a larger sample size. With a more in-depth analysis of the system's potential it could offer valuable evaluation of the ergonomics of different types of shoes as well as their comfort and wearability in diverse contexts. Extensive tests, however, are further needed to fully validate the system and prove its potential.

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