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Wearable and Smartphone-Based Sensors in Support of Human-Comfort-Driven Structural Analysis of Building Components [†]

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Abstract: The continuous progress and advancement of innovation in technology and development of digital tools makes modern structural engineers and technicians of the building and construction sector increasingly able to solve a multitude of design issues. In most of cases, they can take advantage of, and support from, low-cost and even portable sensors characterized by generally medium-high accuracy and commercial availability. In this paper, the attention is focused on the analysis of recent investigations which have been carried out within the scope of human-comfort-driven structural analysis and design of building components. More precisely, the use of wearable and smartphone-based sensors for the experimental derivation of mechanical parameters of utmost importance and technical interest for the design of pedestrian systems is explored. On the one hand, as shown, the elaborated setup makes it fast and easy to acquire body motion parameters for pedestrians moving on different substructures. At the same time, relevant feedback could possibly be obtained from customers on their corresponding comfort.

Keywords: wearable sensors; smartphone-based sensors; biometric parameters; structural design; human reactions; human comfort; experiments

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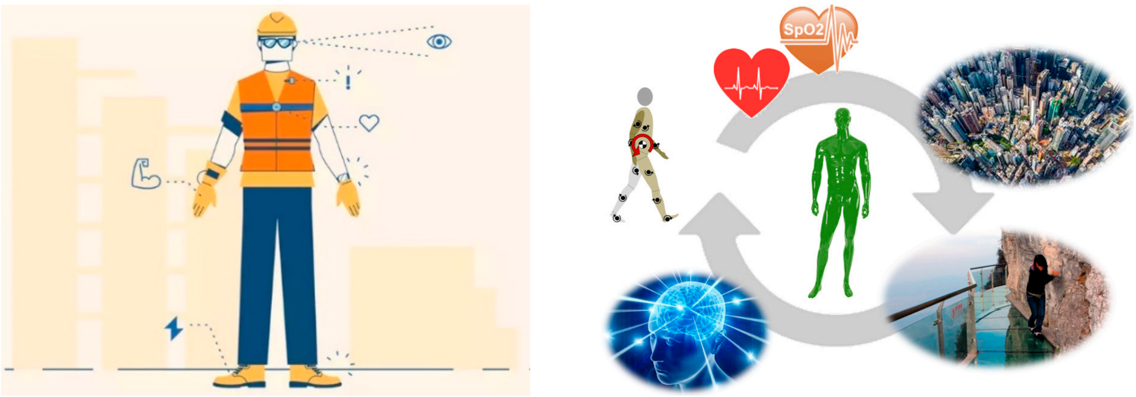
1. Introduction

Worldwide, it is generally recognized that human comfort in buildings and constructions is a target for a multitude of reasons and in multidisciplinary aspects [1,2]. In the same way, however, there is a clear view of uncertainties and complexities which are intrinsically involved in comfort analysis and optimization. In truth, the definition of human comfort itself is rather wide [3–5], and thus necessitates specific design assumptions and performance indicators, such as measures to optimize thermal, acoustic, lighting, and even vibration serviceability aspects, among others.

Overall, a major advantage in the construction sector has been offered, especially in recent years, by a multitude of sensors and devices which are commercially accessible, often low-cost, and aimed at supporting specific activities and consequent decisions. Wearable and smartphone-based sensors can be found in daily activities, and can be optimized as health-monitoring tools but also to improve human well-being against potential risks. Safety, in this sense, is a primary target for those operations in which humans can be potentially subjected to danger and risk of injury (Figure 1a). Typical examples can take the form of (i) smart watches (for health and activity monitoring, fall detection, and safe communication); (ii) smart boots (able to detect pressure from shocks and falls, and inclusive of location sensing); (iii) smart helmets (where sensors can be used to monitor fatigue, prevent microsleeps, detect collisions); (iv) augmented reality glasses (for the identification of hazardous materials and visualization of safety protocols); (v) smart body wears (to track body core biometric parameters); etc. Similar devices can be also intended to be used as sophisticated sensors and instruments in support of engineering issues and problem solving. In this manner, human and biometric parameters are tracked for health monitoring and risk prevention scopes, but can be further exploited as key input performance indicators for structural design, structural health monitoring, functionality and safety maintenance, and structural optimization. As such, it was, for example, shown in [6] that human behaviors on constructed facilities reflect both mechanical and structural conditions and phenomena, but also nervous states and emotional reactions, which are mutually affected by comfort and structural responses (Figure 1b).



(**a**) (**b**)

Figure 1. Wearable and smartphone-based sensors for (**a**) safety on construction sites or (**b**) comfort-driven design (figure adapted with permission from [6] under the terms and conditions of the CC-BY license agreement).

In this context, is it thus possible to use wearable and smartphone-based sensors for coupled well-being optimization and structural design improvement, based on comfort-driven considerations? The question is rather challenging and certainly necessitates wide experimental validation. Moreover, the present research study tries to partly answer this question by taking into account some experimental evidence and the assessment of the typical structural issues of vibration serviceability. How is body motion affected and modified by the built environment? Additionally, how can the structural features of a given load-bearing system modify the behavior of customers?

2. Background and Goal

2.1. Sensors for Human-Comfort-Driven Structural Design

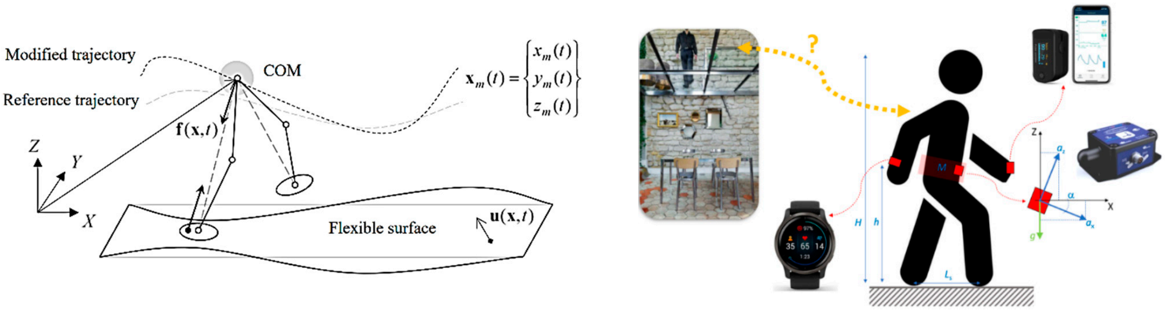
The current investigation starts from the basic consideration that there is a reciprocal and mutual interference and interaction of human behaviors, and thus comfort levels, and the structural features of a given load-bearing system [7,8]. This interaction may result from multiple reasons such as, for example, the aesthetic impact of a construction (and thus emotions [9–11]), or the sensitivity to human motion (such as in terms of perceived vibrations [12,13]), and the subjective reaction of humans to structural responses. This is particularly relevant when "emotional architectures" are the context of human activities [9–11], and in those configurations, glass material has a primary emotional effect on humans, for many reasons [12–15]. According to Figure 1, wearable sensors able to capture specific biometric parameters of customers can thus play a key role in the quantitative measure of human reactions [14,15].

The open question is thus not only how to optimize the comfort of customers against given external actions/conditions, but how we can take advantage of quantitative measure of nervous reactions, emotions, and body motion features to efficiently support the design of those architectures and constructions, and thus integrate traditional and consolidated mathematical models (which are typical of structural/building design) with human parameters.

2.2. Present Elaboration

The overall experimental strategy is based on the assumption that human–structure interaction (HSI) phenomena are intrinsically involved in the design of any kind of pedestrian structure [16,17]. Furthermore, additional basic considerations summarized in Figure 2 are taken into account, namely:

- flexible pedestrian systems involve magnified HSI phenomena on pedestrians [6], and thus their body motion is reciprocally affected by the structural response but also by possible emotional states (Figure 2a and [14,15]);
- wearable sensors can be efficiently integrated into classical instruments for structural health monitoring purposes (Figure 2b and [6,18,19]);
- glass material in buildings and constructions is a critical component to design in terms of structural vulnerability against mechanical loads [20], intrinsic transparency and its emotional effects on customers [14,15], and its intrinsic flexibility and sensitivity to vibrations [13,21,22].



(**a**) (**b**)

Figure 2. Comfort analysis for pedestrians, with (**a**) an example of a possible mechanical model and (**b**) a scheme of pilot protocol for human-comfort-driven design (figures reproduced with permission from [6] under the terms and conditions of the CC-BY license agreement).

Based on the above aspects, this experimental application aims thus at demonstrating that there is a modification of human behaviors on glass floors, and different mechanical reactions are transferred among them during motion, thus both human comfort and structural design are both affected by each other.

3. Experiments on Glass Structures

3.1. Setup

Most of the experimental records during the tests were collected from the author equipped with sensors while walking normally on structural glass pedestrian systems [6,18]. In this regard, it is worth noting that the herein presented experimental strategy also aims to support the assessment of the possible use of low-cost, commercial, wearable sensors in support of tests carried out on various building configurations [6]. Most importantly, the overall analysis is based on the acquisition of body motion features, especially human-induced reaction forces, for the mechanical analysis and quantification of the biodynamic parameters of technical interest for structural design [18].

Among others, the vertical reaction force due to pedestrians is in fact certainly of primary interest. At the same time, it is known that this is rather hard to calculate and can involve the mutual interaction of pedestrians and substructures [23,24]. In the present study, primary attention is hence placed on the experimental derivation, based on commercial sensors, of the well-known Dynamic Load Factor (DLF) corresponding to human-induced reaction forces, which represents a parameter of utmost interest for the structural analysis of floor systems, as well as for comfort analysis and optimization of pedestrians. Most importantly, for structural analysis, average trends of DLF for the examined walking configurations are the primary input for deterministic approaches such as the Fourier series approach, where the DLF is needed to describe the mechanical load on a given structural system. To this aim, three different slab systems as in Table 1 were taken into account (two of them were characterized by transparency and high flexibility).

Table 1. Characteristics of examined floors for experimental measurements during normal walks.

SLAB	Material	Span	Surface	Thickness	Mass	Frequency
		[m]	[m^2]	[m]	[kg]	[Hz]
#1	Concrete	13	110.5	0.80	221,000	>80 [1]
#2	Glass + steel	2.65	4.37	0.04352	460	15.1 [2]
#3	Glass + steel	14.5	40.6	0.04352	4020	7.28 [3]

[1] Vibration frequency estimated by linear modal analysis on an empty floor model; [2,3] experimental vibration frequency values from [17,18].

3.2. Sensors and Records

The present analysis begins with the study concept reported in Figure 2b. In addition, the use of triaxial, Wi-Fi accelerometer, and inclinometer Micro-Electro-Mechanical Systems (MEMS) on the pedestrian's feet is assessed, as it could further facilitate the analysis of body motion during walks. A typical example can be seen in Figure 3, where the vertical acceleration component measured at the author's body center of mass (BCoM) is plotted as a function of time during a walk on a rigid floor. Additionally, the corresponding rotation of the left foot is presented in the Figure. It is worth noting that the rotation angle for the foot is scaled to 1/10th to facilitate the readability of the graphical comparison. For the analysis of DLF trends (amplitudes and sensitivity to floor configuration under the motion of the same pedestrian), three different slabs, as in Table 1, were taken into account during tests.

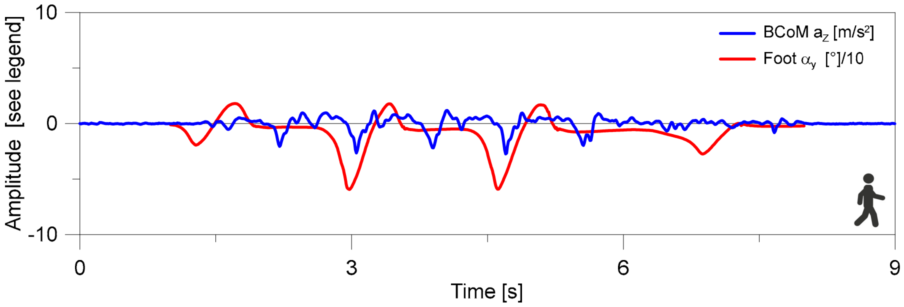
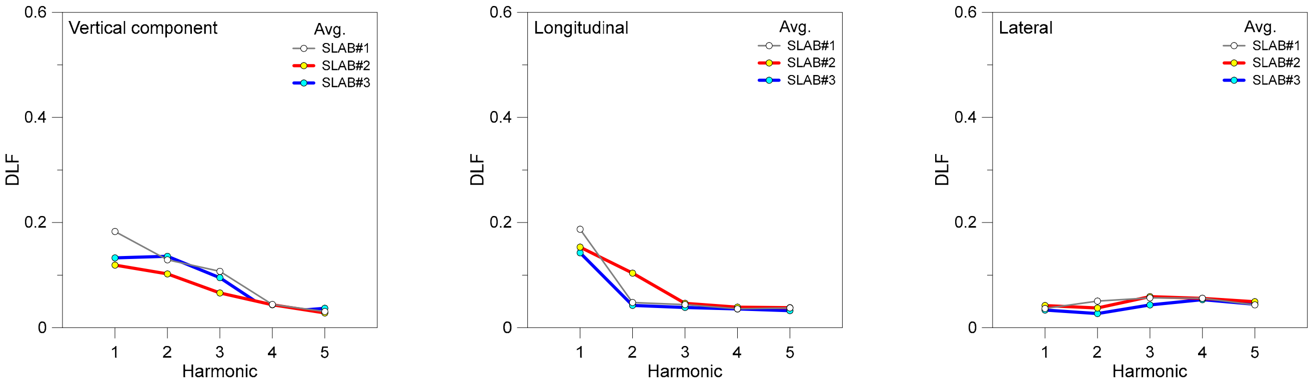


Figure 3. Analysis of body vertical acceleration and foot rotation during normal walking, based on wearable sensors.

4. Experimental Evidence

For the present study, based on experimental records such as those in Figure 3 and others, a major advantage was gained from the use of Matlab® for curve fitting and consequent extrapolation of DLF values. The same operations were repeated over the number of available walking records for harmonics corresponding to vertical, longitudinal, and lateral human-induced loads during motion. In Figure 4, it is thus possible to see the trend of the first five harmonics for the author walking normally on three different substructures, two of them transparent and flexible. The experimentally derived curves are grouped in terms of reaction component. It is important to note that the present evidence is proposed for a fixed walking frequency of f_p = 1.5 Hz for all the examined substructures.



(**a**) (**b**) (**c**)

Figure 4. Average experimental DLF (f_p = 1.5 Hz) for a pedestrian on different substructures. Results grouped for (**a**) vertical, (**b**) longitudinal, and (**c**) lateral components of human-induced force.

The average DLF amplitudes reported in Figure 4 and experimentally derived for the transparent/flexible/lightweight SLAB#2 and SLAB#3 systems are relatively small compared to the rigid concrete system noted as SLAB#1. Furthermore, in Figure 4a it can be noted that the second harmonic of vertical force for SLAB#3 is associated with a higher average DLF compared to the corresponding experimental evidence for the first harmonic. This finding is also in line with several studies in the literature (such as [25–27]), where it has been confirmed that flexible floors with high sensitivity to human-induced effects are characterized by a typically pronounced second harmonic and associated DLF.

The presently elaborated DLF values—based on wearable sensors—are compared with a number of studies in the literature, as can be observed in Figure 5.

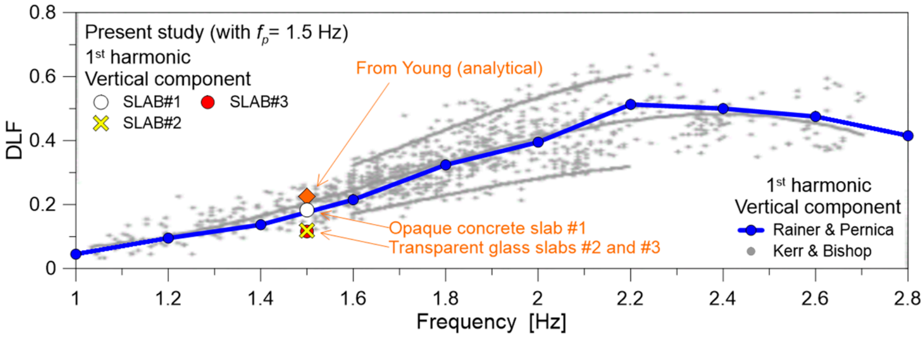


Figure 5. Experimental DLF derivation (f_p = 1.5 Hz) and comparison with experimental evidence in the literature (Rainer and Pernica [25], Kerr and Bishop [26]) or analytical models (Young [27]).

5. Summary and Future Developments

With a focus on the first harmonic of vertical reaction force, it is worth noting that the DLF values elaborated in the present study are in close correlation with the literature, especially for the reinforced concrete SLAB#1. At the same time, it can be seen in Figure 5 that DLF experimental evidence for transparent/flexible substructures (SLAB#2 and #3) is clearly lower than the concrete system, with an average DLF quantified in ≈0.11–0.12 for both, and associated with $\approx -37\%$ DLF scatter towards the rigid/opaque system (#1).

Such a kind of output suggests, on the one hand, that the use of body sensors for integrating structural design performance indicators is particularly efficient (as demonstrated, for example, by a comparison of the literature and the present results on SLAB#1). At the same time, all basic assumptions motivating the present experimental investigation are confirmed in Figure 5, where it can be seen that transparent/flexible systems #2 and #3 involve a marked modification in human behaviors and body motion. Future studies will be thus extended to confirm the present evidence and support the development of a robust methodology in terms of human-comfort-driven structural design optimization.

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