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Pilot Experiments for Multi-Criteria Human Comfort-Driven Structural Glass Design Assessment

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Abstract

Civil engineering design and industry are continuously evolving with the support of advancements in technology. Digital tools are able to assist designers in solving several issues with more accuracy and minimized efforts. In parallel, maximization of human comfort is a target for various design procedures, where mathematical models and standardized protocols are conventionally used to optimize well-being of customers. Major challenges and troubles can indeed derive, structurally speaking, from human reactions, which are related to a multitude of aspects, and may further enforced by slender / transparent glass components. The so-called "emotional architecture" and its nervous feelings are intrinsic part of the issue, and hence the mutual interaction of objective and subjective parameters can make complex the building design optimization. This paper presents some recent studies in which human comfort for glass structures occupants is quantitatively measured, both with the support of remote digital technologies based on facial micro-expression analysis and in-field experiments able to capture kinematic and biometric parameters for customers moving in glass environments.

Keywords

Glass structures, Human reactions, Biometric parameters, Pilot experiments

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1. Introduction

The use of structural glass in the form of transparent load-bearing or secondary components for buildings and open spaces is rather common. Moreover, current architectural demands and new architectural concepts of transparent barriers that have been suggested by the past critical evolution of Covid-19 sanitary emergency, suggest that the use of glass in buildings is further increasing.

Structurally speaking, glass design requires the respect of rigid performance limits and regulations to offer appropriate safety levels in ultimate conditions and human comfort in service conditions. On the other side, are occupants always comfortable in movements and behaviours, when living in glass-built environments? Several studies recalled herein showed, for example, that glass transparency or vulnerability to damage are potential influencing parameters for the reaction of building occupants. Similarly, typical geometrical mechanical properties of glass components for pedestrian systems are often characterized by a minimum of mechanical restraints, as well as by limited thickness compared to size, or structural mass compared to humans. The combination of these multiple aspects is associated to static and dynamic behaviours that often do not match with consolidated mathematical models in use for other constructional typologies. Further, glass aesthetics is also responsible of possible modification in nervous states of customers, and thus evocative of possible modification in normal behaviours. In this paper, results from two different pilot experiments are jointly discussed.

2. Glass structures and human comfort

Several motivations highlight that human comfort in the built environment is a target for a multitude of aspects (Colenberg et al. 2020; Levin 2003). Various engineering tools are typically used to optimize design in terms of thermal comfort, indoor air quality, visual comfort, noise nuisance, ergonomics, and others. Besides, rather limited attention is generally given to other comfort aspects, such as psychological comfort against vibrations, which directly manifests in the form of different behaviours. Many aspects (like, for example, personal factors, nervous states, architectural parameters) are known to represent additional influencing parameters for human comfort in buildings (Figure 1).

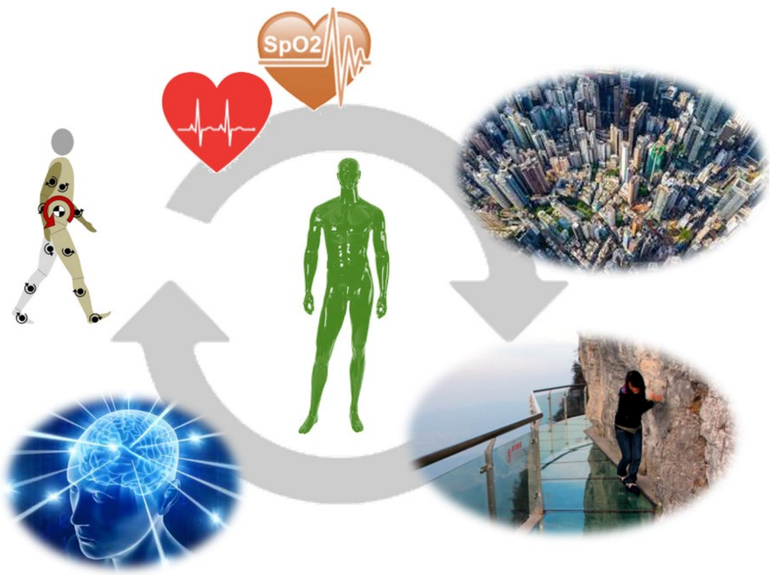


Fig. 1: Qualitative concept of human comfort analysis and quantitative measure in glass-built environments.

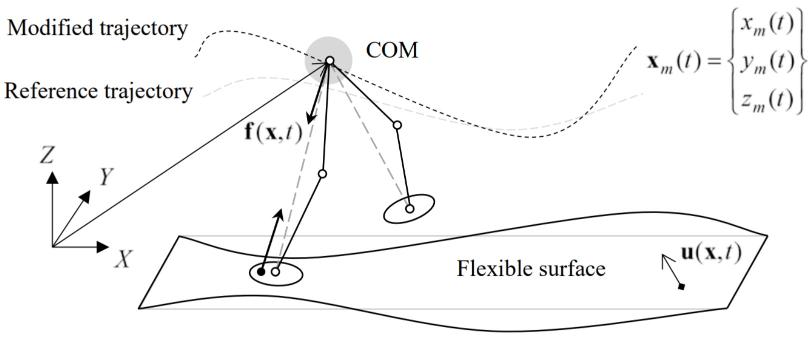
This means that a long list of aspects and parameters are mutually affected by each other, including the correlation of built environment characteristics and its impact on the occupants' emotions, behaviours, and physical well-being (Colenberg et al. 2020). Modification of emotions and nervous state can result for example in different locomotion features (Figure 1), and thus in modification of moving loads which are transferred by humans on structural members. Psychological states are hence potential influencing parameters with a critical role in engineering issues for design, because resulting in possible unfavourable calculation of classical performance indicators (Abdel 2013Yun & Kim 2014; Li et al. 2017; Oldham & Rotchford 1983).

In this scenario, glass components may have a critical role, compared to other constructional solutions. The well-known psychological effect of architecture can in fact have both positive and negative effects on users (Bower et al. 2019). Several architectural concepts are voluntarily expected to evoke nervous states in the so-called "emotional buildings" (Vidal & Abad 2015; Shearcroft 2021).

Among various constructional solutions, this paper gives a special care to structural glass applications in buildings. Known as versatile but vulnerable constructional material, glass transparency and capacity to adapt to various setup configurations make it a largely used solution. Most importantly, glass applications are often known as "architectures of vertigo" (Deriu 2018), where transparent structures are conceived as spaces of visceral thrills and intense psychophysiological stimuli with deep sensory experience and socio-spatial implications. The high aesthetic impact of glass structures can be thus sometimes in contrast with the need of more efficient feeling of protection for the occupants, as it could be for extreme accidents, pedestrian systems, or uncomfortable configurations (Figure 2 (a), (b)).

(a)

(b)



(c)

Fig. 2: Comfort-driven design assessment: (a)-(b) examples of human reactions on glass structures (figures reproduced from (Bedon & Mattei 2021a) under the terms and conditions of CC-BY license agreement), with (c) mechanical model of walking body motion on a flexible system (figure adapted from (Blachowski et al. 2016)).

For facades and building envelopes made of glass, research studies are already trying to address and optimize human comfort especially on thermal issues (see for example (Luna-Navarro et al. 2020; Luna-Navarro et al. 2022). For the specific application of glass pedestrian systems, design solutions can be highly demanding in engineering terms, due to complex human-structure interaction phenomena. Locomotion features for pedestrians walking on rather flexible structures, compared to rigid substrates, is also affected by intrinsic kinematic features (Blachowski et al. 2016, and Figure 2 (c)). As far as nervous states can be evoked by high transparency or even high sensitivity to vibrations and dynamic loads, possible discomfort may arise (Bedon & Fasan 2019). The resulting mutual interaction of mechanical dynamic parameters and motion features due to modification of normal emotional states could manifest in severe changes of subjective reactions, and thus rather uncertain quantitative measure of structural parameters able to preserve comfort (Bedon & Fasan 2019). From a vibration serviceability assessment perspective, possible structural issues and the consequent risk of user discomfort are usually addressed in terms of acceleration peaks under normal walks, towards recommended limit parameters. Such an approach can be based on deterministic vertical loads able to qualitatively reproduce the vertical Ground Reaction Force (GRF) transmitted by human strides on the structure. Recent studies showed however that these conventional loads are potentially unable to capture accurately the structural response of pedestrian systems characterized by limited vibration frequency or high sensitivity to occupants, and may thus result in unsafe structural estimates (Bedon 2022; Bedon & Noè 2022). As a major advantage, different literature studies confirmed that nervous states and emotions could be captured and quantified by facial micro-expressions and optical measures of biometric parameters, also in the case of glass-environments (Bedon & Mattei 2021b). Moreover, the measure of kinematic locomotion features, gait characteristics and biometric features for walking pedestrians can provide additional quantitative correlation of human comfort and structural design.

3. Outlook on ongoing pilot research experiments

3.1. Motivation and goals

It is generally recognized that the definition of comfort levels for building design is rather wide and complex, and structural glass design is even more complex due to the interference of intrinsic material (i.e., transparency, brittleness, etc.) and mechanical aspects (i.e., mass, stiffness, sensitivity to vibrations, etc.). It becomes thus clear that conventional assumptions for structural design – still based on consolidated mechanical concepts – may take advantage of additional tools and technologies to analyse and quantify typical human reactions and behaviours in glass-built environments. The primary goal of present pilot research is hence to address the potential and accuracy of different tools and technological devices to explore and measure the emotional state and body motion of customers subjected to glass environments, so as to possibly support the derivation of reference performance indicators or parameters in support of architectural and structural design.

3.2. Methodology

In order to achieve the prefixed research goals, two different experimental strategies are taken into account. In doing so, multiple response and performance indicators are collected to find correlations in the field of architectural and structural design concepts. For the presently reported results, the first experimental strategy was implemented remotely during Winter 2020 – Spring 2021. The second experimental strategy, characterized by laboratory and in-field measurements, was exploited starting from Autumn 2021.

Remote experimental analysis of human reactions

The first approach consisted in the use of a virtual reality environment in which volunteers were asked to take part to a glass environment presentation and visual stimuli. Major outputs from this first stage of experiment can be found in (Bedon & Mattei 2021a; Bedon & Mattei 2021b). To that end, the FaceReader™ automatic facial expression recognition software (version 8, Noldus Information Technology bv, Wageningen, Netherlands) was used in support of the quantitative analysis of experimental measurements (Figure 3). Two different visual stimuli were designed to assess the reactions of volunteers, namely, consisting of a set of "static" input items and a "dynamic" virtual reality (VR) video clip of pre-recorded walks in glass environments. The post-processing analysis of experimental measurements from was partly based on the automatic FaceReader™ software analysis, and further elaborated as discussed in (Bedon & Mattei 2021a; Bedon & Mattei 2021b). A group of 10 volunteers was actively involved in remote experiments. Video recording of facial micro-expressions, more in detail, was used to detect and measure:

- nervous states and emotions based on facial micro-expressions, and
- Heart Rate (HR) parameters and variations to the imposed stimuli, based on remote photoplethysmography (rPPG) optical technique.

When exposed to a selection of 27 pictures (every 5 seconds) or to a dynamic clip of 120 seconds.

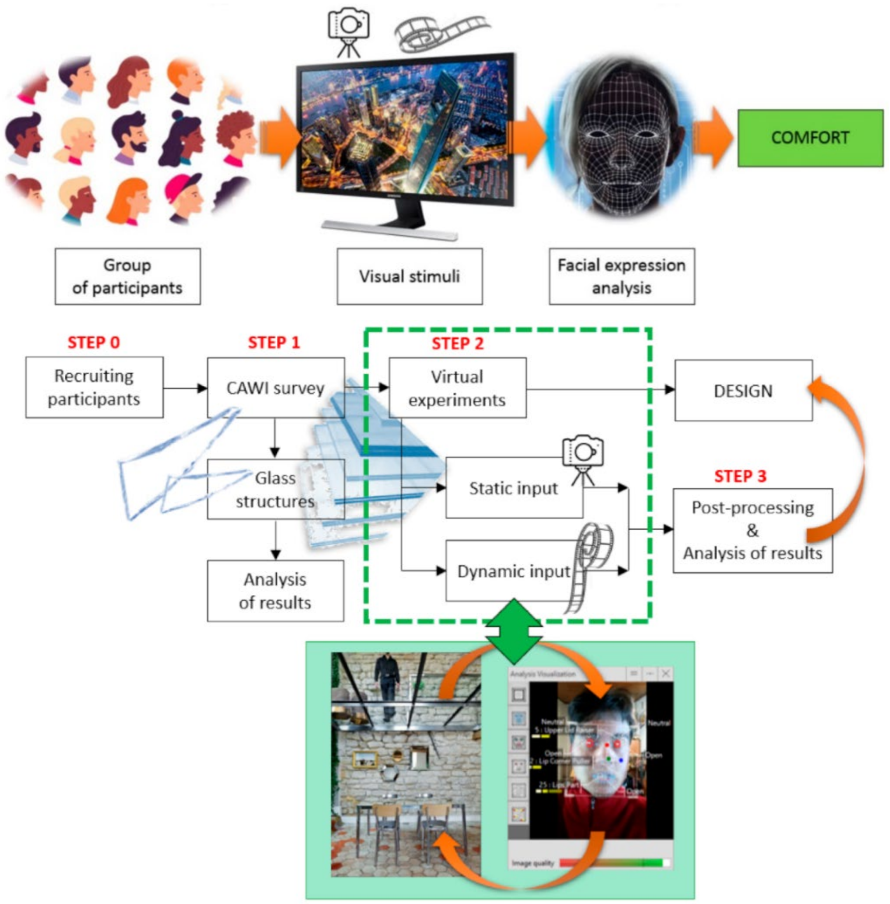


Fig. 3: Experimental setup for the analysis of human comfort based on remote facial micro-expressions and optical HR measurements (figures reproduced from (Bedon & Mattei 2021a) under the terms and conditions of CC-BY license agreement).

Laboratory and in-field body measurements in glass-built environments

The second approach involved the interaction a single volunteer (from the previously defined group of 10) asked to walk in different environments when equipped by several devices able to capture motion kinematics and biometric parameters (Figure 4). For the present pilot study, the attention was given to the combined use of:

- a Wi-Fi triaxial MEMS accelerometer, fixed in the body Centre of Mass (CoM) of pedestrian, to record acceleration components and body CoM inclinations during walks (Bedon & Noè 2022);
- a Bluetooth professional sport watch, to measure walk parameters (speed, gait length) and biometric parameters (HR, SpO2, etc.);
- a Bluetooth finger pulse saturimeter, to capture biometric parameters during walks (HR, SpO2, etc.), for double check of recorded data.

The above instrumentation was used to capture, during normal walking conditions, possible modifications in biometric parameters due to emotional states and potential discomfort, as well as to find possible correlation with kinematic parameters of pedestrians and substructure.

As far as a single Wi-Fi sensor with Bluetooth devices were used as in Figure 4, the advantage of collected experimental records was represented by the lack of connection from any kind of laboratory setup, and thus the simple in-field experimental analysis in different locations and configurations.

Fig. 4: Experimental setup for the analysis of human comfort based on kinematic and biometric parameters (detail photo reproduced from (Bedon & Mattei 2022b) under the terms and conditions of CC-BY license agreement).

4. Experimental results

4.1. Remote comfort analysis

The overall experimental study was initiated with remote measurements developed during Covid-19 restrictions to mobility. Some major outcomes of this experimental phase can be found in (Bedon & Mattei 2021a; Bedon & Mattei 2021b). A primary role was assigned to correlation of HR measures and emotional states towards the assigned glass-related visual stimuli, based also on HR trends for the assigned visual stimuli (Figure 5 (a)).

The analysis of experimental results for the involved volunteers showed a rather good correlation of “negative” emotional states for discomfort and HR modification (bpm increase). This confirms a rather good accuracy of HR analysis and HR variation trends to capture possible comfortable or uncomfortable emotional states in building occupants.

While representative of preliminary outcomes in this direction, a clear correlation was found between specific glass environment configurations and high emotional discomfort for the involved participants. Most importantly, extreme peaks were generally collected for stimuli associated to the presence of:

- outdoor or indoor balustrades (with risk of falling),
- floors and pedestrian systems (with human-structure interaction and risk of falling)
- damage (see for example Figure 5 (b))

In contrary, best conditions were quantitatively measured in terms of emotional states based on facial-micro expressions and HR trends for visual stimuli characterized by the presence of:

- facades and
- roof components without direct contact of participants, or even
- floor systems with comfortable situations for occupants (see the example in Figure 5 (c)).

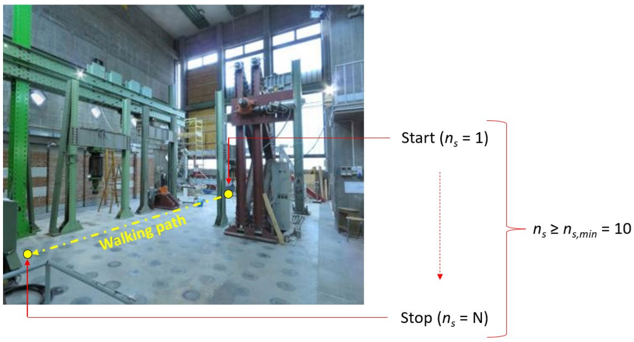
(a) (b) (c)

Fig. 5: Comfort analysis based on (a) remote optical HR analysis for the assigned visual stimuli, with selected examples of static stimuli associated to (b) discomfort or (c) high comfort levels for the majority of involved volunteers (figures reproduced from (Bedon & Mattei 2021b) under the terms and conditions of CC-BY license agreement).

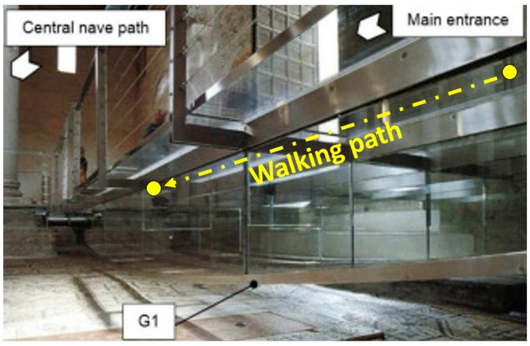
4.2. Laboratory and in-field walks

The pilot analysis and experimental measure was carried out for a single selected volunteer asked to walk on a rigid floor (SLAB#1) and on the flexible slab system (SLAB#2), as reported in Figures 6 (a), (b). These measurements were collected for the volunteer asked to walk naturally, with a rather uniform gait length, frequency and straight path (Bedon 2022). Actually, some further measurements are in progress.

At the time of first trials (Autumn 2021), the rigid SLAB#1 setup was set to coincide with the laboratory environment in Figure 6 (a), and consisting on a massive 80 cm thick reinforced concrete contrast floor. For the analysis of body CoM accelerations on SLAB#2, the suspension laminated glass walkway structurally investigated in (Bedon 2019; Bedon 2020) and reproduced in Figure 6 (b) was taken into account for in-field measurements. The in-service system consists of a composite slab in which the laminated glass section layout includes three 12 mm thick glass panels and inter-posed PVB® foils (0.76 mm thick). An additional glass layer, 6 mm in thickness, is used to protect the laminated section. The glass panels are linearly supported along edges by a metal grid composed of C-shaped steel members. Such a solution is used to cover a total surface of 14.5 m × 2.8 m. The overall slab system is then sustained by four longitudinal steel-glass girders, spanning over the full bending length of 14.5 m. Most importantly, the flexible SLAB#2 system is characterized by a total mass for glass in the order of M_{glass}≈ 4020 kg and a vibration frequency $f_{1,e}$= 7.28 Hz (experimental measure for the empty structure (Bedon 2020)).



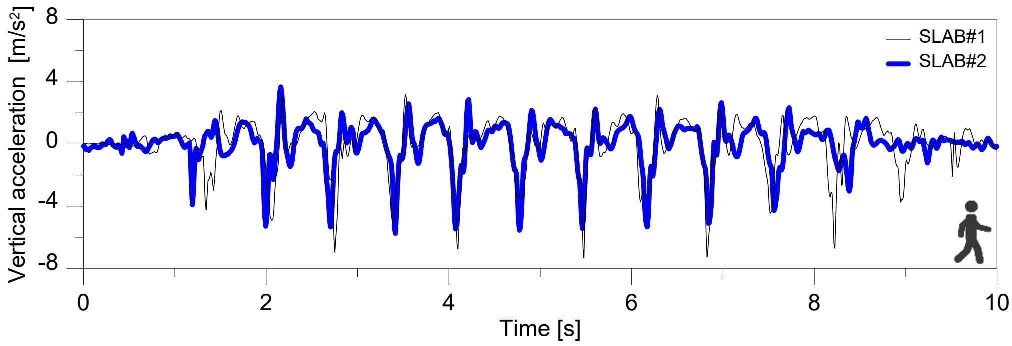
(a) SLAB#1



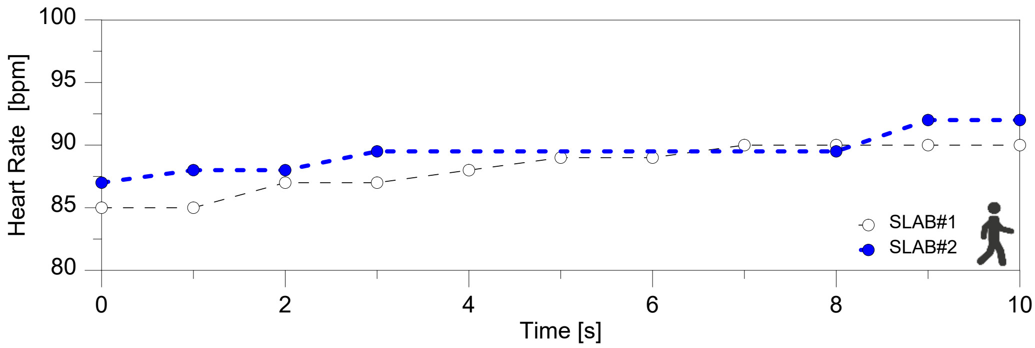
(b) SLAB#2

Fig. 6: Comfort analysis on (a) rigid or (b) flexible substrates (figures reproduced with permission from (Bedon 2022) under the terms and conditions of CC-BY license agreement).

Typical experimental acquisitions from selected walking configurations on SLAB#1 or SLAB#2 can be seen in Figure 7 (a) and (b), in terms of vertical component of body CoM acceleration and HR measurements during walks. The average walking frequency was measured in f_s= 1.46 Hz, which corresponds to a conventional normal-slow motion.



(a)



(b)

Fig. 7: Comfort analysis on different substrates
based on (a) body CoM accelerations and (b) HR trends for the involved volunteer.

It is easy to note in Figure 7 (a) the progressive increase of acceleration peaks from rest, as well as the typical trend of acceleration modules corresponding to each gait repetition. The typical walk consisted in fact of n_s= 15 gaits and was calculated in a walking speed $v\approx$ 1m/s (0.983 m/s), with L_s= 0.67 m the average gait length.

A special attention was first given to the analysis of vertical acceleration component from body CoM reported in Figure 7 (a). From the analysis of whole signals, it was observed that:

- the RMS acceleration value was calculated in 0.441 m/s^2 and 0.444 m/s^2 for SLAB#1 and #2 respectively;
- in terms of acceleration peak (absolute value), this was measured in a_{max}= 7.33 m/s^2 for SLAB#1, while for SLAB#2 the walking records resulted in a_{max}= 5.76 m/s^2. Body CoM acceleration trends in the repetition of modular gaits were also found rather uniform in time but with more pronounced peaks in presence of rigid sub-structure (SLAB#1). Such a comparison corresponds to a +27% scatter for maximum acceleration on SLAB#1 and SLAB#2, thus suggesting a more pronounced human-structure interaction on the flexible system of Figure 6 (b);
- from the above consideration, the average absolute peak during locomotion was also calculated, and resulting in $a_{max,avg}$= 5.56 m/s^2 for SLAB#1 and $a_{max,avg}$= 5.01 m/s^2 for SLAB#2 (values derived excluding gaits 1, 2 and 14, 15 characterized by low speed). This corresponds, in average, a scatter of +11% for body CoM vertical accelerations on the rigid SALB#1 system;
- the peak-to-peak value was also calculated from experimental signals, and again associated to +11.5 % scatter for SLAB#1, compared to SLAB#2;
- finally, the analysis for focused on transversal acceleration peaks associated to body CoM motion (*y*-component in the reference system of Figure 4), compared to the corresponding vertical acceleration peaks for each gait. The transversal component values were generally found smaller than the vertical one, as expected. The effect of different substrate resulted in an average ratio of vertical-to-transversal peaks in the order of ≈0.52 for SLAB#2 and ≈0.67 for SLAB#1 (+28%).

In terms of biometric parameters for the same walking scenarios, an example is proposed in Figure 7 (b), where it is possible to perceive a rather stable trend of HR values with time of walk, but slightly higher values for SLAB#2 rather than SLAB#1. HR increase in the time of experimental is also slightly higher for SLAB#2 rather than SLAB#1.

In this regard, it is important to notice that the in-field experimental pilot study was carried out with a single volunteer (present author) having high confidence with the environment of walks, and thus less affected by possible emotional states. The experimental analysis proposed in (Bedon & Fasan 2019) and carried out in the same location of Figure 6 (b) with a group of external volunteers confirmed that comfort levels and perceptions of vibrations from pedestrians moving or standing on glass systems with relatively low vibration frequency are highly subjective. This means, on one side, that a huge number of data is needed to derive general observations. At the same time, findings in (Bedon & Fasan 2019) confirm that nervous states can strongly affect body motions and human behaviours, and thus strong modifications are expected for records in progress, compared to Figure 7.

For the present experimental setup, finally, no important modifications were noticed in SpO2 values (96-98% the range of variation during experimental walks), nor in HR trends based on the two Bluetooth devices in use. As a result, the present outcomes can be seen as a validation of instruments and concept layout for future experimental measurements with large groups of volunteers.

5. Summary and conclusions

The optimization of human comfort in the built environment is a target for several design fields and applications, but rather challenging issue, given that it depends on a multitude of aspects and interactions. For structural engineering applications, mathematical models and simplified procedures can allow to take into account conventional models of building occupants (i.e., deterministic stride loads, etc.), but these models can present intrinsic weakness.

In this paper, the attention was focused on the use of technological devices and tools to measure quantitatively some body parameters for customers, with the aim of assessing their human reactions and interactions with glass-built environments. Two different pilot experimental approaches, based respectively on the measure of human feelings and nervous states with facial micro-expressions and optical heart rate trends, as well as on the use of Wi-Fi and Bluetooth devices to capture body kinematics and biometric parameters for customers, have been presented.

At this present stage, the analysis of remote experimental outcomes (with a group of 10 involved volunteers) confirmed that human reactions may suffer for psychological discomfort especially for customers asked to interact with glass load bearing components characterized by possible risk of fall (like for example balustrades, pedestrian systems, etc.). Such an outcome was also partly confirmed by in-field measurements for an involved volunteer asked to walk on a rigid substrate or a more flexible (and thus sensitive to vibrations) transparent glass floor. In this latter case, however, laboratory and in-field measurements were carried out for 1 volunteer only (from the group of 10).

In this sense, such a kind of pilot experiments emphasized the need of large sets of measurements to quantify and correlate human comfort trends and needs to classical mechanical parameters in use for structural glass design. Further volunteers will be necessarily involved to extend the discussion of parametric outcomes. Most importantly, different operational conditions and building scenarios will be experimentally explored to try generalize the experimental output of different volunteers.

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