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# Structure-to-Human Interaction (H2SI): Pedestrian Response to Oscillating Footbridges and Considerations on Their Structural Control and Health Monitoring

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**Abstract:** This review paper investigates the current state of research on structure-to-human interaction (S2HI) in the monitoring and control of cyclo-pedestrian footbridges, focusing specifically on the biodynamic effects of oscillations on pedestrians. Its aim is, therefore, twofold: In the first half, it examines the limited but evolving understanding of human gait responses to vertical and horizontal vibrations at frequencies and amplitudes characteristic of footbridge dynamics. The second half includes a detailed analysis of various modelling strategies for simulating pedestrian and crowd dynamics, emphasising the movements and stationary behaviours induced by structural vibrations. The aim is to highlight the strengths and limitations of these modelling approaches, particularly their capability to incorporate biomechanical factors in pedestrian responses. The research findings indicate that existing studies predominantly focus on human-to-structure interaction (HSI), often neglecting the reciprocal effects of S2HI, with many results in the literature failing to adequately address the biomechanics of single pedestrians or crowds experiencing structural vibrations on cyclo-pedestrian bridges. This gap underscores the need for more precise and comprehensive studies in the field to improve the understanding of dynamic interactions between single or multiple walking individuals and footbridge vibrations, especially for vulnerable and elderly people with limited mobility. Furthermore, considerations regarding the impact of Structural Control and Health Monitoring to alleviate these issues are briefly discussed, highlighting the potential to optimise footbridge performance in terms of pedestrian comfort.

**Keywords:** footbridges; human–structure interaction; vibration; human gait; crowd behaviour; human dynamic load modelling; structural control; structural health monitoring

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## 1. Introduction

The topic of structure-to-human interaction (S2HI) has gained increasing importance in the design, monitoring, and control of cyclo-pedestrian footbridges. While the broader concept of human–structure interaction (HSI) has been extensively studied, particularly in light of high-profile events, such as the closure of the London Millennium Footbridge due to excessive lateral vibration on the day of its opening on 10 June 2000 [1] and the case of the Solférino Bridge, where the same occurred in 1999 [2], there has been growing interest in understanding the reciprocal dynamics of S2HI.

S2HI focuses on how structural vibrations, whether vertical or transverse, influence the mechanical and physiological responses of pedestrians. This perspective moves beyond the traditional focus on human-to-structure interaction (H2SI), which refers to how the mechanical properties of a single-human or crowd behaviour change the dynamic response of a structure [3] and where the impact of human loads on bridge dynamics is typically analysed. S2HI investigates how pedestrians, either individually or as part of a crowd, adjust their gait and internal driving forces (consciously or subconsciously) in response to surface oscillations, leading to changes in induced forces and gait patterns [4]. Despite its interdisciplinary appeal, combining structural, biomechanical, and psychological aspects, S2HI remains underexplored in the scientific literature compared to H2SI. While several studies have addressed the effects of pedestrian-induced forces on bridge dynamics, fewer have investigated how the vibrations, in turn, alter pedestrian biomechanics.

The aim of this review is to merge the different facets of the issue, including a dynamic point of view, as well as to highlight the inaccuracy and the limits of the current approach due to the lack of experimental studies [5] and appropriate tools, despite the recent attempts to have a comprehensive view of the matter. This unreliability is strongly dependent on the impossibility of considering all the inter- and intra-subject variability of the pedestrian and/or the crowds: Recently, many physical and even statistical models have been adopted to predict all the possible effects of this variability on the structures, but still, they struggle to capture the key features of S2HI and HSI [6].

In this sense, this review paper will not directly touch on how HSI considerations can influence footbridge design; from a civil and structural engineering standpoint, the current state-of-the-art of this aspect (which, as mentioned, is lacking in terms of S2HI perspective) is well addressed by many recent contributions in structural vibration serviceability such as [7–9].

The remainder of this article is organised as follows. Section 2 recalls the key points related to the vibrational behaviour of slender, lightweight pedestrian bridges. A few notes on the current regulations are reported as well, to provide the needed context. Then, the first half of this paper deals specifically with the biomechanical perspective of the problem: Section 3 introduces the topic of human gait in response to bridge vibrations; Section 4 analyses in detail the impact on walking pedestrians of vertical footbridge vibrations, reporting the current understanding of how the human gait responds to these external vibrations; and Section 5 reports similar findings for lateral bridge vibrations.

Since the two problems of S2HI of HSI are too intertwined to be discussed separately, the second part of this manuscript reviews (respectively, in Sections 6 and 7) single-human and crowd (multi-person) modelling strategies as proposed by several authors.

Finally, Section 8 addresses the potential uses of SCHM apparatuses to counterbalance excessive human-induced vertical and horizontal vibrations on slender, flexible footbridges, and the Conclusions Section (Section 9) highlights the key findings of this review work.

Therefore, the intent of this paper is to cover both the structural and (especially) the biodynamic side of the problem, focusing on footbridge vertical and lateral vibrations and their effect on standing and walking pedestrians, as well as reporting some considerations on how Structural Control and Health Monitoring (SCHM) procedures can be employed to reduce these negative effects.

## 2. Footbridge Vibrations, Regulations, and Impact on Walking Pedestrians

Since the late 20th century, there has been a rise in the construction of elegant, long, and slender footbridges, which often face the risk of resonance at low excitation frequencies. The reason for this is quite simple: Considering the bridge dynamics as a discrete multiple degrees-of-freedom (MDoF) model, limited to $M$ dominant modes of interest, one has that its natural frequencies will be defined by

$$\omega_n = \sqrt{\frac{k_n}{m_n}}, \tag{1}$$

where $\omega_n$ is the natural pulsation (in rad/s) of the $n$-th mode $(1 \leq n \leq M)$, and $k_n$ is its corresponding modal stiffness, defined by

$$k_n = \varphi_n^T \boldsymbol{K} \varphi_n. \tag{2}$$

And, similarly, $m_n$ is the corresponding modal mass, given by

$$m_n = \varphi_n^T \boldsymbol{M} \varphi_n, \tag{3}$$

where $\boldsymbol{K}$ and $\boldsymbol{M}$ are the square $M$-by-$M$ stiffness and mass matrices of the dynamic system's model and $\varphi_n$ is the $n$-th mode shape. These infrastructures are characterised by flexible structural materials, such as steel, and a very high slenderness ratio (the effective length of the element with respect to its cross-sectional dimensions), meaning that their vertical and horizontal flexural stiffness is very low. Therefore, for transversal vibration modes (either vertical or lateral), low $k_n$ results in low $\omega_n$. These are not comparable with even slender infrastructures such as long-span suspended or cable-stayed steel-made bridges, where natural frequencies can reach down to $f_n = 0.05$ Hz (see one example in [10]), but are in the same order of magnitude as many conventional R.C.- and mixed R.C.-steel-made road bridges (see e.g., [11,12], with fundamental modes at ~4 Hz and ~2.5 Hz, respectively), which are much stiffer but also much more massive. The use of innovative building materials, such as glass fibre-reinforced polymer (GFRP) composite deck slabs—which are becoming more common in lightweight bridges [13]—makes the accurate estimation of the bridge dynamics even more challenging [14].

However, differently from any other infrastructure, cyclo-pedestrian footbridges are characterised not only by low cross-sectional stiffness but also by a low or extremely low mass per linear metre (in the order of 1000 kg/m [15]). Therefore, the structure is not only slender but generally very lightweight. Therefore, the total mass and stiffness (and even the damping [16]) of such footbridges under operational conditions are affected in a proportionally significant way by the presence of pedestrians and bicycles, either by their static effects (i.e., their added weight and stiffness when still) or by their dynamic loads when moving [17]. This changes the dynamics of the infrastructure in a non-negligible way.

Not only that, the range of footbridge natural frequencies, both lateral and vertical, often coincides with the dominant frequencies of the human-induced load. This can cause several issues, such as the ones already discussed for the famous cases of the Millenium [18] and Solférino Bridges [2,19], whose images are shown below in Figures 1 and 2, and more recently, for the Squibb Park Bridge in Brooklyn in 2014. Specifically, in the Millenium Bridge case, the resonance between the external excitation and the bridge structure led to swaying movements that caused discomfort among pedestrians and necessitated its temporary closure for modifications. This was due to the suspension pedestrian bridge's design, which resulted in a particularly low lateral stiffness, making it prone to vibration-induced comfort problems in that direction. The incident highlighted the importance of accounting for pedestrian-induced vibrations in bridge design and the need for effective mitigation strategies.

**Figure 1.** Millennium Bridge in London (UK) looking north.

**Figure 2.** Solférino Bridge in Paris (FR) looking north.

Other noteworthy full-scale, field case studies of human-induced footbridge vibrations include the Changi Mezzanine Bridge at Singapore Airport [20], the Pedro and Inês Bridge in Coimbra, Portugal [21,22], the Toda Park [23] and Maple Valley Great Suspension [24] bridges in Japan, the Simone de Beauvoir footbridge in Paris [25], and finally, the Infinity Bridge in Stockton-on-Tees [26] and the Clifton Suspension Bridge in Bristol [26] (both in the United Kingdom). However, these cases are far from rare: The first documented pedestrian bridge incident dates back to April 12, 1831, when one of Europe's first suspension bridges, the Broughton Suspension Bridge, collapsed due to dynamical instability induced by marching troops. Nevertheless, this seems to be the only reported case of a bridge reaching its ultimate state because of human-induced dynamic loads. The prevailing wisdom since is that soldiers should avoid marching in step, in case their stepping frequency might resonate with a natural (vertical) vibration frequency of the bridge, and it is now established practice that soldiers are given the command to "break step" upon crossing a bridge.

Regarding the external excitation force, one can refer to biomedical research works to establish the frequency of human gait, i.e., the rate at which a person takes steps while walking or running, typically measured in strides per minute or hertz (Hz). Key findings from the current state-of-the-art indicate that, for healthy individuals, the stride frequency for walking generally ranges from approximately 48 to 76 strides per minute, which translates to about 0.8 Hz to 1.26 Hz [27,28]. That is also known as the 'preferred walking speed', which is around 1.4 m per second (approximately 5 km/h) for most adult individuals. In contrast, during running, the frequency can increase up to 214 strides per minute (or about 3.57 Hz) depending on the speed and individual capability [28]. These considerations all derive from scientific studies over large cohorts of tested participants, such as the one reported in [29]. However, walking and running stride frequency are influenced by various biomechanical factors, including joint and muscle forces, stability considerations, and energy expenditure. As individuals age or experience joint issues, their preferred stride frequency may decrease due to changes in physical capability.

Today, it is generally accepted that vibrations generated by human dynamic loads typically pose more of a serviceability concern rather than a safety issue related to structural strength. This is because human activities generally introduce forces with low amplitude. Yet, on the other hand, humans are remarkably sensitive to vibrations, even to amplitude levels as low as 0.001 mm [30]. Such high sensitivity often causes vibration serviceability issues long before the vibration levels reach thresholds capable of compromising the structure's integrity [31].

In this sense, the human body is reportedly capable of adapting quickly to almost any type and level of vibration by changing its walking pattern [32]; this leads to a change in the distribution of forces on the vibrating surface [33]. In particular, it becomes a problem as the process of synchronisation occurs: This process prompts individuals to synchronise their steps with the oscillation and each other, creating a positive feedback loop that amplifies even the slightest initial oscillation [34]. When this happens with a crowd, the effect on the structure begins to be noticeable (even if still far from causing rational structural issues, it becomes large enough to cause irrational panic among the pedestrians involved).

In this regard, it is important to remark that the dynamic loading from human walking is mainly vertical. In comparison, human-induced lateral vibration in a bridge is expected to be much less impactful on the bridge. Concerning these lateral dynamic loads, walking always follows a lateral zigzag motion, whose dominant frequency is about 1 Hz, as the human walks by periodically shifting the weight from one foot to the other. However, as mentioned previously, the magnitude of the lateral force from human walking is an order of magnitude smaller than the vertical force [23,35].

To address the issue of pedestrian-induced vibrations in footbridges, numerous studies have been conducted, focusing on three main areas:

1. The characterisation and modelling of pedestrian dynamic loads,
2. The prediction of responses to various loading scenarios, and
3. The establishment of comfort criteria for assessing and limiting vibrations.

However, there are only a few significant contributions regarding the comfort criteria aspect, and the matter is still, for the most part, limited to scientific research only (see e.g., the paper collection in [36]). Although many international codes provide loose guidelines or stricter regulations for evaluating footbridge comfort under pedestrian dynamic loads, each has its shortcomings. Some codes do not reference relevant research on footbridge vibrations [31], while others use a single acceleration threshold to distinguish between acceptable and unacceptable vibrations, often ignoring frequency dependency. Given the subjective nature of comfort, it is more reasonable to assess people's perceptions of vibrations using multiple gradations [37]. Internationally, there are two approaches to addressing the vibration serviceability limit state for bridges. The first approach ensures that the lower frequencies of bridge vibrations fall outside the frequency ranges associated with typical pedestrian pacing rates. The second approach limits induced structural accelerations to levels below prescribed acceptable limits [38]. However, especially in more developed countries, the increasing interest in the topic is rapidly inducing new research and more updated guidelines; a recent example can be found in the 2009 JRC technical report released by the European Commission on the design of lightweight footbridges for human-induced vibrations [39].

Recent developments in the area of lateral excitation of footbridges indicate that bridges with a fundamental vertical frequency above 5 Hz and a fundamental lateral frequency above 1.5 Hz are considered to meet vibration serviceability requirements. These limits, which are similar to those used in other codes of practice, are well-defined. However, relying exclusively on these limits would prevent the construction of lightweight landmark structures. For frequencies below these thresholds, some codes of practice define acceptable vibration levels in terms of allowable peak accelerations; Blanchard et al. [40] set the maximum permissible vertical acceleration at $0.5\sqrt{f_0}\,\mathrm{m/s^2}$ where $f_0$ is the fundamental natural frequency of vertical vibration. This limit, based on human sensitivity to vibrations, is a compromise between the relatively low vibration levels acceptable for humans on bridges, as proposed by Leonard [41], and the levels of vibrations reported by Smith [42] as required to impair normal walking [43].

## 3. Human Gait in Response to Bridge Vibrations

Human locomotion constitutes a complex activity, also affected by the person's specific aims while walking. Researchers offer various hypotheses about human movement goals: Some suggest that the motion aims to minimise the movement of the human centre of mass while walking; others propose that humans flex their leg joints to reduce shock and vibration. Additionally, some argue that humans seek to minimise the variability of accelerations in the head and pelvis, or that the innate objective is stability. Despite these differing hypotheses, it is widely recognised that human locomotion is a cyclic activity characterised by features such as pacing frequency, stride length, and stride width [43].

In this context, 'gait dynamics' refers to the temporal and spatial characteristics of walking, including parameters like step length, cadence, and walking speed. When pedestrians perceive vibrations, they adjust these parameters to maintain balance and stability. In fact, the study of pedestrian-induced vibrations has revealed that structural vibrations can alter gait characteristics, leading to synchronisation phenomena where pedestrians inadvertently match their walking rhythm to the bridge's oscillations—the so-called "lock-in" effect [33], which may happen for either vertical [44,45] or horizontal [46] oscillations.

For instance, they may shorten their steps or slow down to mitigate the effects of vibrations. This adaptation can impact the overall walking pattern, leading to increased energy consumption and potential discomfort. However, research indicates significant variability in how individuals respond. For instance, Brady et al. [47] introduced an experimental scenario where healthy adults walking on a laterally oscillating surface exhibited two primary responses: Some opted to maintain their position in space while allowing the surface to move beneath them, while others anchored themselves to the surface, moving with its oscillations. The degree to which individuals adopted these extremes varied. This suggests that adults possess innate and diverse preferences for optimising gait stability, with some relying more on visual cues (maintaining position in space) and others on proprioceptive feedback (anchoring to the surface).

Similarly, 'kinematic variability' refers to the fluctuations in the movement patterns of limbs during gait. Walking on oscillating surfaces increases kinematic variability, indicating a higher demand on the neuromuscular system [48]. While this variability can signify adaptability, it also presents a potential risk factor, especially challenging for individuals with compromised motor skills, like the elderly or those with disabilities [49]. Research indicates that individuals with better motor skills and balance are more proficient at adapting their gait to vibrations. However, even they may experience heightened kinematic variability under significant vibration conditions. For vulnerable populations, the impact can be more severe, potentially elevating the risk of falls and other injuries, compromising their health and safety.

To study human gait and related phenomena in response to bridge vibrations, researchers generally use experimental or analytical approaches or a combination of the two methodologies. Experimental approaches typically involve the use of instrumented walkways, motion capture systems, and force plates to measure the gait parameters and kinematic variability of pedestrians as they walk over vibrating surfaces. For example, Bocian et al. [50] investigated the spatial and temporal characteristics of pedestrian loading on a full-scale structure. They employed a wireless inertial reference system affixed to a foot, as shown in Figure 3, comprising tri-axial accelerometers, gyroscopes, and magnetometers, to gather data while pedestrians traversed an instrumented treadmill positioned at the midspan of a flexible bridge. From these data, they developed a pedestrian loading model utilising a single-point inertial measurement from the wearable system. Proprietary software of APDM (Motion Studio, version 1.0.0.2015) was used for system calibration and data retrieval.

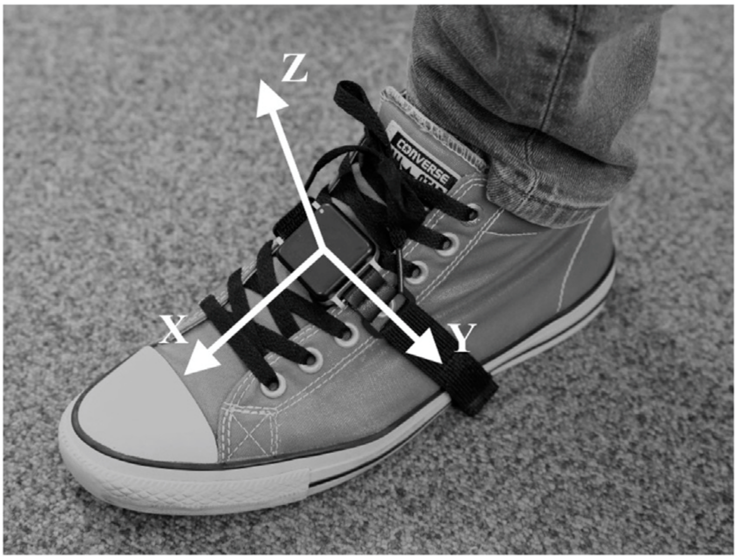


**Figure 3.** AHRS attached to a foot used for PDR (pedestrian dead-reckoning, a navigation technique used to determine the position and orientation of a walker [51]). Retrieved from [50].

As for the analytic approaches, Aux et al. [52] proposed a novel three-dimensional model for human–structure interaction (HSI), integrating a biomechanical representation of the human body with a structural model of a simply supported beam. This framework allows for a precise assessment of the influence of surface vibrations on human gait. The system's dynamics were analysed through a combination of inverse dynamics to estimate human motion and direct dynamics to solve the differential equations governing the interaction. Gait predictions, including body movement and ground reaction forces, were derived using only three basic gait parameters—average walking speed ($V_w$), step frequency ($f_w$), and step length—alongside anthropometric data and structural characteristics. This streamlined approach demonstrates the model's capacity to analyse and predict human responses to structural vibrations effectively, offering insights into optimising both pedestrian comfort and structural performance.

Biomechanical considerations also allow to limit the frequency range of interest: On the one hand, as mentioned, humans are sensitive to even small-amplitude mechanical oscillations with frequencies ranging from well below 1 Hz to at least 100 kHz, a range even broader than that of human hearing. However, only oscillations at the lowest frequencies, between 0.1 and 5–10 Hz, are characteristic of large man-made structures such as tall buildings, large ships, and long suspension bridges, which may transmit vibrations to people. The frequency range from about 3 to 30 Hz includes various types of vibrations commonly encountered in everyday life, such as those from vehicles, machinery, and building components like walls, floors, and house frames, often caused by wind loads, seismic activity, impacts, or vibrating forces. Such vibrations are often accompanied by noise, making it challenging to distinguish whether the disturbance is primarily due to mechanical vibrations or acoustical components. At frequencies above 30 Hz, typical of the responses of lighter building elements like small panels, windows, and room fittings, human sensitivity to vibration becomes secondary to the response to audible noise [53]. Therefore, for the remainder of this study, the interest was set on studies focused on bridge vibrations below 10 Hz.

Importantly, while numerous studies have examined the effects of either vertical or horizontal vibration, the combined impact of both types remains largely underexplored, especially in the context of standing pedestrians (most research focuses on seated individuals). Thoung and Griffin [54] investigated a method for predicting discomfort in standing people due to simultaneous fore-aft, lateral, and vertical vibrations of the floor. However, they concluded that no single, straightforward approach could accurately predict discomfort across all stimuli, as the rate of discomfort increases with the intensity of the vibration, depending on both its frequency and direction. Only very recent studies are currently focusing on experiments that involve both vertical and lateral vibrations, such as the one reported in [55], which addressed the dynamic coupling between vertical and horizontal gaits, as well as the respective pedestrian-induced loads, and the responses of the structure.

## 4. Pedestrian Responses to Vertical Bridge Vibrations

When experiencing sinusoidal vertical oscillation at frequencies below approximately 2 Hz, most parts of the body move together up and down. This movement creates a sensation of being alternately pushed up and then floating down. The eyes can either track moving objects along with the body or adjust to focus on stationary objects. If the motion frequency is below 0.5 Hz, it may eventually cause symptoms of motion sickness, such as sweating, nausea, or vomiting [56]. For individuals in a seated position, vertical oscillation at frequencies above 2 Hz can lead to amplification of the vibration within the body. The resonance frequency, where this amplification is greatest, varies between different body parts, individuals, and postures. The first major resonance typically occurs around 5 Hz, where the driving force per unit acceleration (apparent mass) reaches its peak, causing the most discomfort.

In a standing position, which is of more interest when referring to walking pedestrians, the effects of vertical vibration are often similar to those in a seated position. However, as Matsumoto and Griffin investigated [57], bending the knees can significantly reduce the impact of frequencies above 3 Hz. Regarding the study of vibration amplitude's effect on the perception of a standing body, most researchers do not focus on discomfort: Kiiski et al. [58] examined the transmission of vertical sinusoidal vibrations to the human body across a wide range of amplitudes and frequencies, aiming to assess vibration-induced accelerations.

They identified a critical threshold amplitude of 0.5 mm, which could lead to dangerous peak accelerations, even at higher frequencies. Most studies analyse myoelectric activity to identify which combinations of parameters (frequency and amplitude) enable purposeful muscular stimulation, as seen, for example, in the work of Pollock et al. [59].

However, the impact of pedestrian structure's movement in the vertical dimension on human gait remains largely under-investigated. Analytical approaches often involve the development or the employment of existing mathematical models to simulate the dynamic interaction between pedestrians and bridges. These models can help predict the response of both the pedestrian and the structure under various conditions. Gheitasi et al. [60] adopted both experimental and analytical methodologies to address the issue. Peak accelerations were calculated according to prevailing design standards and then compared to comfort thresholds. Findings from both experimental and analytical investigations indicate that the footbridge exhibits acceptable serviceability performance under conditions of low and moderate traffic density. However, the comfort level during periods of very dense traffic loads was rated as minimal based on the outcomes of analytical calculations. Recent studies in ergonomics [61] have established specific thresholds for discomfort caused by vertical vibrations. For instance, research indicates the lowest possible vertical acceleration threshold as low as approximately 0.03 $\mathrm{m/s^2}$, where 50% of respondents begin to report discomfort. Also, the discomfort experienced by pedestrians is highly dependent on the frequency of the vibrations; at frequencies above 30 Hz, the discomfort caused by vertical vibrations can be significantly more pronounced, especially at higher magnitudes (1.0 to 2.5 $\mathrm{m/s^2}$). In particular, the same study found that the rate of increase in discomfort correlates with both the magnitude and frequency of the vibrations, indicating that current standards may underestimate discomfort at higher frequencies. This aspect is critical for assessing the comfort levels of pedestrians on bridges subjected to vibrations induced by walking or jogging.

## 5. Pedestrian Responses to Horizontal Bridge Vibrations

Currently, the effects of horizontal whole-body vibrations at the amplitudes and frequencies typical of pedestrian bridges are even less studied than those of their vertical counterparts. It is, however, known that horizontal oscillations induce a different set of sensations at the level of human perception. At frequencies below approximately 1 Hz, the oscillation tends to cause the body to sway, but this can be countered by muscular effort, helping to maintain a relatively stable upright posture. In the 1–3 Hz frequency range, stabilising the upper body becomes challenging, and discomfort due to vibration acceleration is at its peak. As frequency increases, horizontal vibration is less effectively transmitted to the upper body, and thus, the perceived discomfort decreases [56].

An interesting study assessing multiaxial S2HI effects under lateral vibration conditions has been recently conducted by Castillo et al. [62]: This research employed the Human–Structure Interaction Multiaxial Test Framework (HSI-MTF) alongside a cost-efficient motion capture system using smartphone technology. This setup featured an instrumented treadmill placed on a shake table, enabling the simultaneous analysis of pedestrian-induced gait loads in both the vertical and lateral directions during sinusoidal lateral motion of the surface. The findings showed that lateral vibrations significantly impacted gait mechanics, leading to shorter support times as individuals adapted their movements to maintain balance. The study also emphasised the individual variability in S2HI effects, even under identical vibration conditions. Regarding load dynamics, maximum lateral loads ($L_L$) normalised to the individual's weight ($W_0$) increased linearly with higher vibration frequencies, with the rate of increase amplified by greater vibration amplitudes. Conversely, vertical loads ($L_V$), also normalised to $W_0$, remained consistent for vibration amplitudes up to 30.0 mm but exhibited a linear rise in response to higher frequencies beyond this threshold.

The consequences of exposure to side-by-side horizontal vibration are multifaceted: The perception of motion, resulting sensations, and impacts on health and activities are intricate phenomena. Vibration often leads to multiple, overlapping outcomes, such as discomfort, task interference, and potential injury risks. For instance, Baker et al. [63] investigated the effects of horizontal whole-body vibration and standing postures on task performance. Their study revealed that the time taken to complete the task increased as vibration intensity rose. Additionally, the fore-and-aft posture showed more significant performance declines and postural disruptions than the lateral posture, with performance being better during vertical vibrations compared to horizontal vibrations.

Vibration's impact on the body is complex and nonlinear, depending on how the vibrations are transmitted through the body and which muscle groups are affected. Current research has primarily focused on isolated cases, examining the effects of specific frequencies and/or amplitudes, but these findings are difficult to generalise. Postural changes can influence how vibrations are transmitted to the body, thereby affecting the severity of their harmful effects. To the best of the current knowledge, it seems that pedestrians typically begin to experience discomfort when lateral accelerations exceed approximately 1.0 to 1.2 $m/s^2$ [64]. At these levels, individuals may alter their gait or stop walking altogether due to discomfort.

## 6. Single-Human Modelling

By far, the most studied aspect within the field of both s2HI and HIS concerns human modelling, which involves selecting the most appropriate way to represent the human body as a physical model.

Currently, there are various proposed models that describe human behaviour in response to bridge vibrations. However, none of them are completely exhaustive, partly because many studies focus solely on either lateral or vertical oscillations. Therefore, the models they develop are not sufficient to explain the physical phenomenon comprehensively, as both types of oscillation often occur simultaneously. Furthermore, concerning actual modelling, research divides the study of single-human models and crowd models. That is to say, there is no generalised approach that can be applied to specific cases of either single or multiple pedestrians.

### 6.1. Single-Human Vertical Vibration

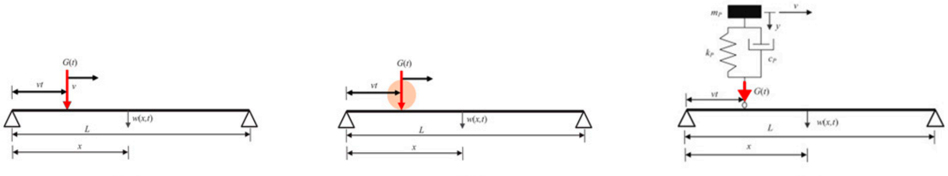
The single-human vertical vibration model can be broadly categorised into three main families: moving force models, where the study of pedestrian-induced vertical vibrations involves treating the pedestrian as a moving force, i.e., considering the pedestrian as a concentrated load that travels at a constant walking speed; dynamic interaction models, which incorporate one or more biomechanical characteristics of pedestrians, which can be as simple as their mass or complex gait dynamics parameters (see e.g., [65]), to more realistically address the interactions with the bridge; and finally, pseudo-excitation methods, which allow for the assessment of walking variability on footbridge vibrations by simulating random walking patterns.

At present, the main international standard that provides a model for the single-pedestrian walking load is ISO 18649 [66], which gives an approximate description of a pedestrian's movement on a bridge. Arguably, the most comprehensive definition of comfort is described in the German guidelines [67], which not only consider the firm load and lateral load but also select different load patterns according to different population densities.

Regarding vertical vibrations, these are generally much more studied than lateral ones. This derives from a key design point: Large-span floor slabs and bridge structures typically have lower vertical, rather than horizontal, stiffness, thus making them more susceptible to significant vibrations induced by vertical pedestrian loads, which can subsequently lead to comfort-related issues (nevertheless, as already mentioned for the Millenium Bridge, it is undeniable that horizontal pedestrian forces also exhibit noticeable periodicity and can induce lateral vibrations in structures).

Caprani's work [68] summarises and analyses some models, cataloguing them as moving force (MF), moving mass (MM), and moving spring–mass–damper (SMD) systems. However, Ref. [68] does not consider other types of models, such as the inverted pendulum, distributed mass, and bipedal.

In this review work, the models presented in Caprani's work are analysed first. The first and simplest one is the MF, which only models the weight force on a beam hinged at both ends, as can be seen in Figure 4a. It is immediately noticeable that by doing so, important characteristics such as mass, stiffness, and damping are neglected. However, current guidelines, such as Eurocode 5 [69] or BS 5400 [70], use this model as a reference.



(a) (b) (c)

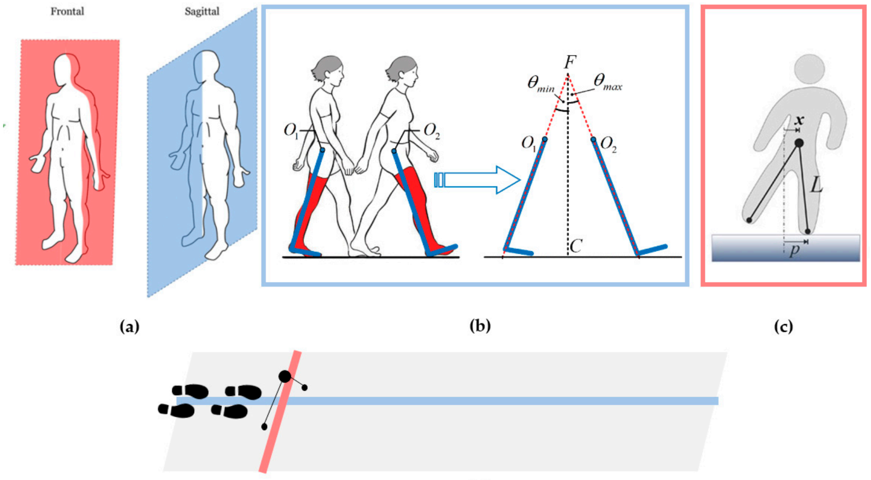
**Figure 4.** Single-human models, as discussed in Caprani [68], showing a simply supported beam as a simplification of a footbridge structure: (**a**) MF model of a pedestrian; (**b**) MM model; (**c**) SMD model. The black arrows indicate the direction of motion, while the red ones indicate the point of application.

Interestingly, this simplified approach resembles the one prescribed by several national norms, such as the Eurocode 1, for the axle load models of moving vehicles (i.e., cars and trucks) on bridges [71].

On the other hand, the MM model, presented in Figure 4b, was first introduced by [72] and used in several works, including e.g., a well-known study by O'Sullivan [73]. Unlike the MF model, the moving mass model considers the inertia given by the pedestrian's mass. However, it presents a critical point: It assumes an equal deflection of the pedestrian's centre of mass and the bridge surface. The last model discussed in Caprani [68] is the SMD model, depicted in Figure 4c. In this case, the human body is represented as a mass supported by the parallel of a spring and a damper. Among these three very simplified models, this is the one that more faithfully represents the body's tissue properties in damping and absorbing vibrations and is currently one of the most used models. This was also validated by Caprani in terms of finite element simulations, which found that the first two models overestimate the bridge's response, while the SMD is quite faithful. However, it is more complex to calculate the parameters (stiffness and damping coefficient) needed for using this model with respect to the two other simplest models seen before.

In this sense, Shahabpoor et al. [74] discusses that in many studies, for example [75–77], using the SMD model, stiffness and damping values are assumed by the authors or taken from biomechanical studies related to other human activities rather than walking. In the same study, the author proposes experimentally obtained frequency f and modal damping ratio $\zeta$ values, which are very reliable as they reflect the values obtained by Silva et al. [78], who conducted an independent study.

Moving to more recent works, another model is the inverted pendulum, as proposed by Belykh et al. [79] and only briefly mentioned in Caprani [68]. This model consists of a mass positioned at the person's centre of gravity, supported by two rigid legs considered massless. Importantly, this model can be applied to investigate either the vertical and/or lateral vibrations induced by the axial (forward) or the transversal (lateral) movements of a single pedestrian; for instance, in Figure 5, an example of the inverted pendulum model can be seen applied to the pedestrian's lateral forces. However, as for many other applications, the use of this model seems to be limited to the decoupled models; to the best of the authors' knowledge, no study with the use of a slanted inverted pendulum in a 3D setting was found.



(a) (b) (c)

(d)

**Figure 5.** The inverted pendulum models of a pedestrian: (**a**) body axes; (**b**) forward movement, adapted from [80]; (**c**) lateral movement, adapted from [79]; (**d**) hypothetical model in a 3D environment for combined use.

The inverted pendulum has the advantage of easily obtaining dynamic parameters (displacement, velocity, etc.) and is described by a second-order differential equation [79]:

$$\ddot{x} + f(x_i, \dot{x}_i) = -\ddot{y}, \tag{4}$$

where $\ddot{y}$ indicates the effect of the bridge on the $i$-th walker, $x_i$ is the independent variable that describes the space of the lateral movement made by the $i$-th walker, while $\dot{x}_i$ and $\ddot{x}_i$ are, respectively, its first and second time derivative, i.e., velocities and accelerations, thus,

$$\ddot{y} + 2h\dot{y} + \omega_0^2 = -r\sum_{i=1}^{n} \ddot{x}_i, \tag{5}$$

where $h$ is a dimensionless damping coefficient, $\omega_0$ is the natural frequency of the bridge loaded with $n$ walkers, and $r$ represents the strength of the coupling between the walkers and the bridge.

However, the drawback is that the amplitude of a pedestrian's walk depends on initial conditions, determined by the size of the initial step, even if it is too large or too small. In practice, the solutions obtained from solving the differential equation are not sinusoidal like sine and cosine but hyperbolic functions. Therefore, Belykh et al. [79] proposes using a system of two differential equations, each describing the behaviour of one of the two feet, to make it a harmonic oscillator.

$$\begin{aligned} &\ddot{x} + \omega_0^2(p - x) = 0,\ if\ x \geq 0\ (\text{rightfoot}) \\ &\ddot{x} + \omega_0^2(-p - x) = 0,\ if\ x < 0\ (\text{left foot}) \end{aligned} \tag{6}$$

where $\omega_0 = \sqrt{\frac{g}{L}}$ is the pulsation of the system.

A less common model is the spring-damped bipedal model, which is also seeing recent uses in other biomedical modelling taks for human walking (see e.g., [81]). For applications to slender footbridges, in Qin et al.'s study [82], the pedestrian is described with a mass placed at the centre of gravity, as in the inverted pendulum (see Figure 6). However, the legs, still considered massless, are depicted as the parallel of a damper and a spring per leg, making it a system with two degrees of freedom. Each spring and damper acts independently of the other elements, and the author only considers their influence on the model's dynamics when the forces of springs and dampers oppose gravity. It is interesting to note that among the analysed studies, this is the first one where a biomechanically similar human walk is considered. In previous studies, authors have always represented walking simply as a displacement in one direction at a constant speed, ignoring the vertical displacement of the mass or the angle between the forward-leaning leg after a step and the bridge surface.

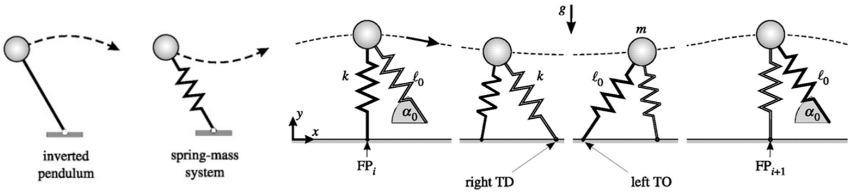
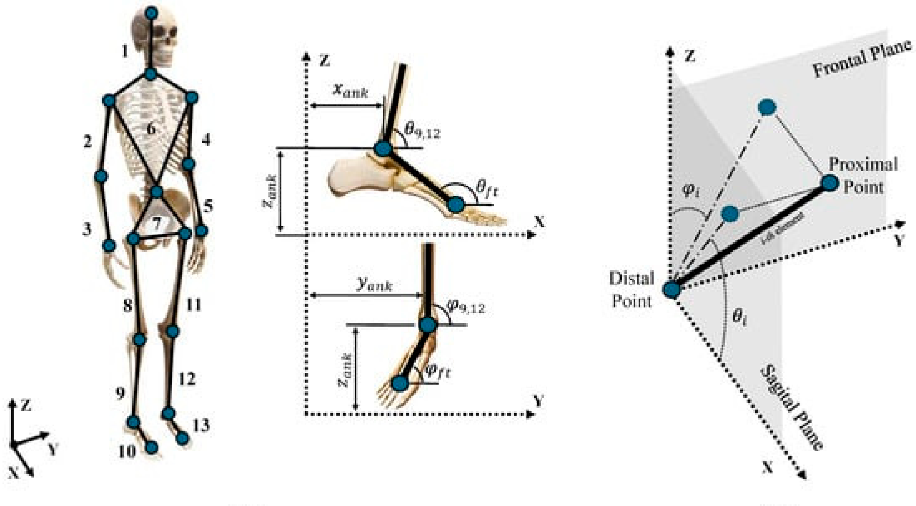


**Figure 6.** Schematic of the spring-damper bipedal (biomechanical walking) model ($\theta_0$ is the angle of attack), also compared with the kinematics of an inverted pendulum of the same length.

In the same study, it is also shown through numerical simulations that during walking, if leg damping increases, then the walking frequency decreases, approaching the natural frequency of the walkway. The limitation of this study is that a human's legs do not change as in the simulations, i.e., nonlinearly, but in a way currently unknown to the author [82], which can substantially affect the human response. Now, in the authors' opinion, also based on the current scientific consensus, the bipedal model is the biomechanical model that most accurately describes walking and can also be used for running, as suggested in Geyer et al.'s study [83]. Even more complex approaches have been proposed in more recent years, such as the many-joints systemrecently put forward in [84], or the biomechanically inspired model presented in [52], which included 13 rigid elements (body segments), connected by joints that allow free rotation in the three body planes (sagittal, frontal, and coronal), as shown in Figure 7.



(a) (b)

**Figure 7.** Body segments (**a**) and their spherical coordinates (**b**) as investigated in [52].

To conclude, all the models seen so far considered the pedestrian as a single-degree-of-freedom (SDoF) system; it is worth recalling that some works used MDoF models (see, e.g., [85]), even if the actual advantages of these more complex models are debatable.

### *6.2. Single-Human Lateral Vibration*

Regarding the study of lateral vibrations of footbridges, many studies focus on quantifying the GRF (ground reaction force) produced by pedestrians walking, generating oscillations, and then establishing models that can describe their behaviour. The study conducted by Ricciardelli et al. [86] provides important considerations. First, their experiment demonstrated how models based on the periodicity of forces during walking are incorrect. Furthermore, a new model is proposed using a stochastic approach. Through an experiment where volunteers had to walk on a treadmill, the GRF of each participant was acquired, and it was noted that they were not periodic. This non-periodicity means that walking cannot be explained through a Fourier series. Therefore, to overcome this difficulty, the authors have proposed a stochastic approach instead of a deterministic one, which better describes the phenomenon [86]:

$$\frac{S_{(FL)k}(f)f}{\left(\boldsymbol{F}_{\boldsymbol{Li}}^{2}\right)\boldsymbol{k}} = \frac{2A_i}{\sqrt[2]{2\pi}B_i}\exp\left[-2\left(\frac{\frac{f}{if_1}-1}{B_i}\right)^2\right], \tag{7}$$

where $\left(F_{Li}^{2}\right)k$ is the energy of the process at that particular harmonic, $A_i$ is the parameter used to normalize the power spectral density, $B_i$ is the bandwidth parameter, and f is the frequency of the harmonic.

Macdonald [46] demonstrates how the inverted pendulum model is suitable for describing the GRF generated by a pedestrian walking on a stationary bridge. However, this study is valid only in cases where the pedestrian does not change the step frequency and does not resonate with the bridge, the bridge does not undergo large oscillations, and finally, the pedestrian does not change the way to maintain lateral balance.

Han et al. [87] present a recent and significant study that introduced a new mathematical model to examine the lateral forces generated by pedestrians, using the London Millennium Footbridge as a real-world example. The model considers pedestrian traffic moving in both directions, with walking modelled as a periodic motion characterised by a $2\pi$ cycle, where each step corresponds to a phase increment of $\pi$. Furthermore, the lateral forces exerted by individual pedestrians are treated as independent of the bridge's movement. The proposed model effectively captures the lateral oscillations of the Millennium Footbridge, showing that the step length and initial phase synchronisation of pedestrians have minimal impact on the bridge's dynamic behaviour.

Furthermore, it is worth recalling the study by Strogatz [88], which has not been included in this section only because it uses the model already described in the previous paragraph for the lateral vibration as well.

In conclusion, the current trend in single-human modelling (concerning both vertical and lateral oscillations) is leading towards more sophisticated biomechanical models, mostly thoroughly examined in laboratory experiments under controlled conditions and using extensive wearable sensing devices. These complex models are characterised by many body parts, modelled as rigid links between 3D joints, as well as many other biomechanical parameters calibrated from experimental observations. However, future research should focus on more nuanced models that consider individual variations in gait and movement patterns, to develop frameworks that can predict individual and population-level responses to vibration exposure [89].

## 7. Crowd Modelling

For the so-called ‘lively’ footbridges, with many individuals moving from one bridge end to the other one in one or two directions (see a pictorial example in Figure 8), it is more convenient to drop the single-human model and focus on a statistical representation of crowd–structure interactions. In this regard, the literature primarily identifies three types of descriptions of crowd behaviour. The first type is macroscopic, which considers the flow of people as a fluid and is based on conservation equations to obtain an evolution equation for mass, linear momentum, and energy. The second type is microscopic, which corresponds to modelling the dynamics of each individual pedestrian in the crowd, which mainly comprises four different categories, as reported in [90]:

- The social forces models,
- The cellular automata models,
- The rule-based models,
- The agent-based models.

This paper focuses solely on describing a social force model for the microscopic type, as it is currently the most suitable for various types of situations, despite not accounting for pedestrian decision making [91]. While multi-agent models are more realistic and complex, as shown in [90,92–94], to the best of the authors’ knowledge, no studies have employed this type of model to investigate vibrations caused by crowds. Finally, the third type is statistical, which involves creating an equation that describes how the probability of a pedestrian’s position and speed changes along the path.

In this review, at least one study for each type of modelling was analysed, examining their strengths and weaknesses.

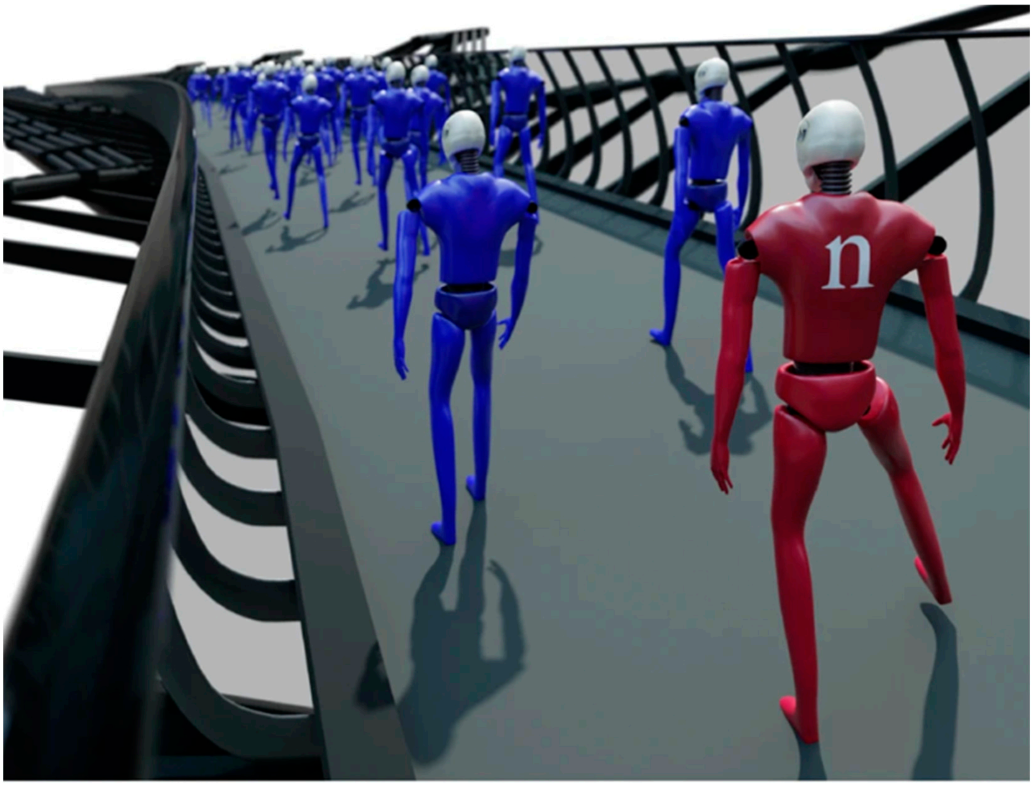


**Figure 8.** Pictorial representation of a crowd moving in one direction. Retrieved from [95].

A mathematical model proposed by Venuti et al. [96] is the hydrodynamic model, where the bridge is described as a one-dimensional beam and the walking crowd above it is also treated as a one-dimensional compressible fluid. The reference equation used to describe the behaviour of the crowd is the one-dimensional mass conservation equation in Eulerian form:

$$\frac{du}{dt} + \frac{d(uv)}{dx} = 0, \tag{8}$$

where $t$ is the independent temporal variable, $x$ is the independent spatial variable, $\rho$ is the mass density of the crowd, and u is the crowd velocity. Finally, the parameter q, which is the linear mean flow, is defined as $v \times u$. The study highlights that the lack of experimental data does not allow for defining a specific closure equation for pedestrian flow. Therefore, the authors proposed three different qualitative equations in accordance with the literature.

Despite this method being able to describe discontinuities in crowd flow, such as congestion or obstacles in the path, it remains a qualitative model due to the previously mentioned lack of experimental data. The previous model is criticised by Carroll [97], as it does not consider the evolution of pedestrian crowd behaviour. In his study, adopting a microscopic modelling approach, the author proposes a crowd model based on the inverted pendulum, modelling each pedestrian separately and according to this model. Based on these assumptions, the authors conducted numerical simulations and finally attempted to describe the actual oscillations of the Clifton Suspension Bridge. Initially, 240 static pedestrians modelled as inverted pendulums, as seen in the previous Figure 5, were randomly generated on a bridge and then made for walking in place. In this paper's results, it was shown that, if the system is stable, the energy input from the crowd is dissipated by the structure. However, when instability develops—achieved, in this case, around 520 s—the energy increases more rapidly than the structure can dissipate.

In this case, the behaviour of the model closely approximates that observed on various full-scale bridges; however, so far, the pedestrians have not had the opportunity to interact with each other. The complete model proposed by the author, in fact, considers the behavioural modifications of the crowd and is based on the previously mentioned inverted pendulum and on behavioural rules called social forces [98], which act on each individual mass like real forces and they underlie variability inter- and intra-subject, because, basically, variability inter-and intra-subject is due to differences between the walking velocities, masses, and acceleration between pedestrians, as stated in [99]; in this way, considering them, the model is more complex and realistic.

Regarding the social forces, these are described in detail in Carroll's work [100], using the assumptions made in [98].

Despite being more computationally expensive, this model has several advantages:

- It allows for maintaining accuracy even at low traffic density.
- It eliminates the velocity–density relationship for the crowd as it tends to move naturally.
- It provides the ability to define individual parameters for each pedestrian.

However, there are some issues when it is applied to the oscillations of the Clifton Suspension Bridge. The proposed crowd model effectively describes the crowd only when it is very dense and of short duration, such as during peak hours. In contrast, it is less accurate when the crowd is more relaxed, and there are more interactions between individual pedestrians.

The second critical point concerns the pendulum inverse model itself. The author hypothesises that when the bridge undergoes lateral oscillations, pedestrians manage to maintain balance by adjusting their posture during their step. This is crucial because predicting the foot position requires knowledge of the position and velocity of the centre of mass. However, if pedestrians adjust their balance due to oscillations, this information is compromised.

However, there are no studies confirming or refuting this phenomenon. Therefore, further research is needed to provide empirical justification for the inverse pendulum model.

In one of the most recent studies conducted by Venuti et al. [101] to investigate crowd-induced vibrations, the software MassMotion 9.5 is used to model individuals as moving masses. The software treats pedestrians as intelligent and autonomous entities, so they tend to take the shortest path to reach their destination; thus, when the geometric environment is created by the software, each pedestrian autonomously calculates the fastest route through which to move.

After selecting the best path, the MassMotion software calculates the direction and speed of each pedestrian using a social force algorithm based on three main points:

- Acceleration towards the desired velocity;
- Repulsive terms to avoid collisions;
- An attractive term towards other people or objects.

The numerical results obtained show that the average walking speed is strongly dependent on the width of the path, especially when the bridge is narrow, and the crowd density is low. In these cases, average speeds tend to decrease with decreasing width. Conversely, with high crowd densities, the average walking speed is not affected by the width of the bridge. The paper reports how the results obtained in [101] are consistent with others retrieved from the pre-existing literature—specifically, [51,52,102–105].

Using traffic flow theory, Li et al. [106] developed a model of crowd-induced random vibration, which responded well to the numerical simulations presented in the study; however, some simplifications were made, making the model incomplete. For instance, the step of the crowd was considered uniform, and the influence of pedestrian movements among themselves when the crowd density varies was ignored. In this model, indeed, the random walking of the crowd appears as a series of identical loads acting on every point of the bridge, with the same time interval between two adjacent points.

That led to a two-way crowd-walking model. Taking an average load, a series of random time intervals between pedestrians walking along the bridge is generated, thus creating a temporal sequence of forces generated by N pedestrians described by the following equation:

$$F_s(t) = F_{e1}(t) + \sum_{i=2}^{N} F_{ei}\left(t - \sum_{j=1}^{i-1} t_j\right),\ t \geq 0, \tag{9}$$

where $F_{ei}(t)$ is the single foot force of the $i-$th pedestrian.

Since all pedestrians are assumed to have the same step frequency, the power spectral density of the load depends only on the average time interval between pedestrians. Thus, bridge vibration can be studied solely from these two parameters.

The studies analysed so far have always considered significant oscillations both vertically and horizontally, without considering an important human dynamic: panic, which can occur during the movements of the structure, especially when there are numerous people on the footbridge. First, it is necessary to understand what is meant by a panic situation. As reported in the study by Helbing et al. [107], there are some characteristics that distinguish these situations: People's movements become much faster and more disordered, causing collisions between them; blockages are created near the main escape routes, neglecting secondary exits; and finally, the escape can be slowed down by fallen or injured people who are seen as obstacles.

If a crowd resonates with a footbridge and very significant oscillatory movements are created, these behaviours could worsen this type of situation. However, as far as the authors know, no study has ever taken this issue into account.

In conclusion, in the current state, the integration of biomechanical models into crowd dynamics is very limited, but it is slowly gaining traction. This approach would enable a more detailed understanding of how individual and collective movements affect bridge dynamics, providing insights into crowd behaviours. Other current trends include a more extensive use of machine learning prediction, also including data retrieved from multiple physical domains via sensor fusion, to statistically analyse the crowd behaviour (even if sometimes at the cost of not investigating any further the biomechanical physics behind these behaviours). As a potential future direction, in the authors' perspective, the crowd models will need to integrate more physics-informed concepts from the human gait, as well as insights from social psychology, to integrate the root causes of crowd dynamics rather than solely rely on statistical formulations of the resulting phenomena.

## 8. Structural Control and Health Monitoring Strategies for Vibration Mitigation

As of today, many pedestrian and cyclo-pedestrian bridges are continuously monitored worldwide; a few examples are reported in Figure 9.

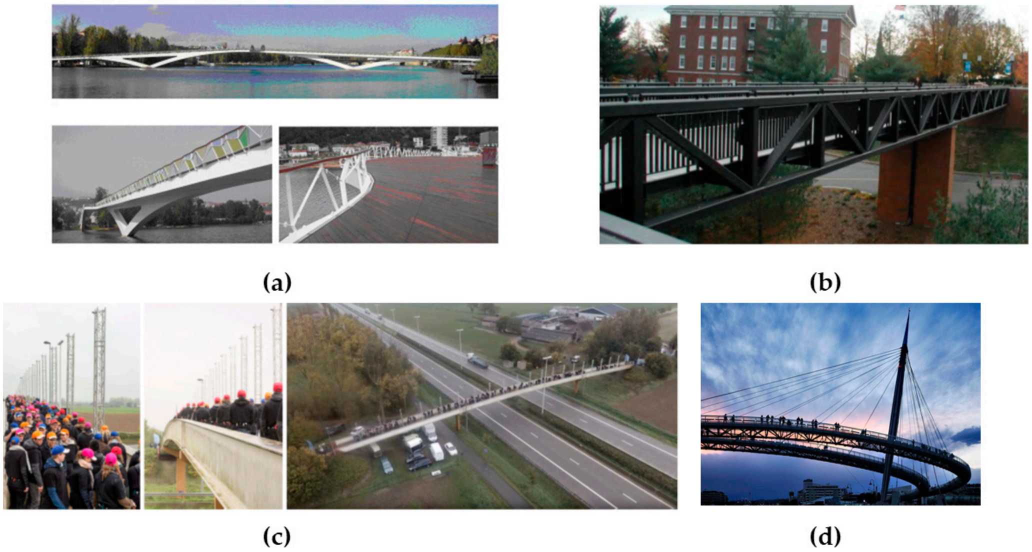

(a) (b) (c) (d)

**Figure 9.** Some examples of dynamically monitored slender footbridges: (**a**) the Pedro e Inês footbridge (from [108]); (**b**) the Downing Hall footbridge (from [109]); (**c**) the Eeklo footbridge (from [110]); and (**d**) the Ponte del Mare footbridge in Pescara, Italy.

In this regard, several strategies can be employed to mitigate the impact of pedestrian-induced vibrations on bridges. These strategies can be categorised into structural and non-structural approaches.

Structural approaches include the following:

- Increasing stiffness: Designing bridges with higher stiffness can raise their natural frequency [111], reducing the likelihood of resonance with pedestrian steps. This can be achieved by using materials with higher stiffness or incorporating design elements that enhance the overall rigidity of the structure. However, this is not always feasible, as stiffening the bridge could be economically or practically unfeasible or be deemed too impactful on its aesthetic and/or functionality.
- Dampers: Installing dampers, such as viscous dampers or tuned mass dampers (TMDs), can effectively reduce the amplitude of vibrations. These devices absorb and dissipate energy, preventing the build-up of excessive oscillations. The use of tuned mass dampers, shown in Figure 10, was instrumental in mitigating vibrations on the Millennium Bridge, by making the bridge capable of dissipating more energy without the need for stiffening [112].

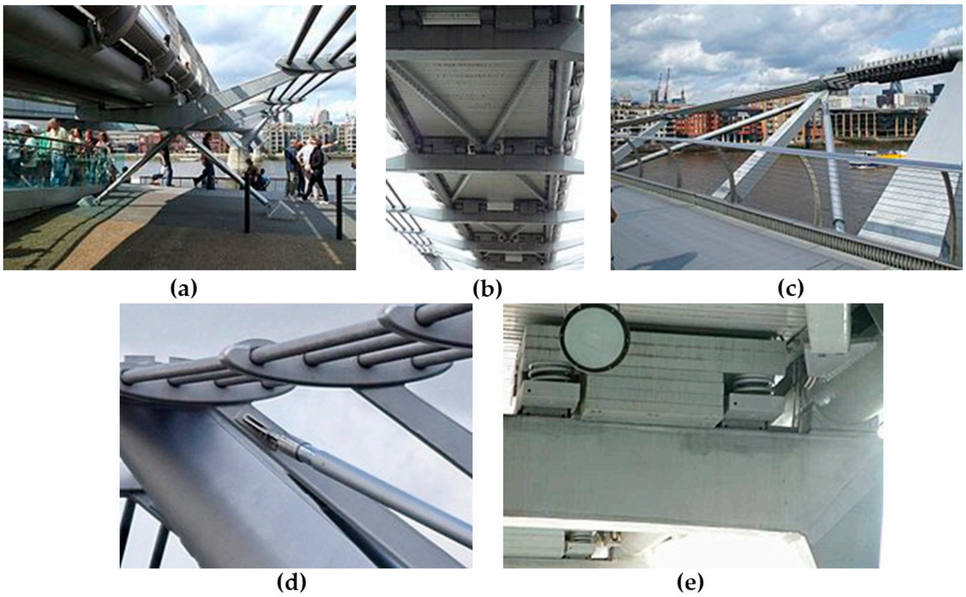


**Figure 10.** The several kinds of dampers set on the Millenium Bridge after the 2001–2002 retrofit: (**a**) vertical-to-ground dampers; (**b**) chevron dampers; (**c**) pier dampers; (**d**) moving end of pier dampers; (**e**) TMDs.

Non-Structural approaches include the following:

- Crowd management: Implementing crowd-control measures during peak usage times can help distribute pedestrian loads more evenly, reducing the likelihood of synchronisation and resonance effects. Techniques such as staggering pedestrian traffic and controlling the flow can significantly reduce vibration issues [113].
- Public education: Educating the public about the effects of their walking patterns on bridge vibrations can help mitigate the impact, and informing pedestrians about the importance of avoiding synchronised walking can reduce the likelihood of accidentally inducing resonance or, at least, avoid panicking.
- Real-time monitoring: Smart bridge technologies incorporating sensors and real-time monitoring systems can provide valuable data on human–structure interaction. These systems can detect unusual vibration patterns and trigger automated responses to mitigate risks, ensuring the safety and comfort of pedestrians [114].

However, Structural Control and Health Monitoring (SCHM) can provide a valid solution for human-induced vibration management on lightweight and slender cyclo-pedestrian bridges. Such systems, indeed, can apply the advantages of both structural and non-structural mitigation approaches.

That is to say, dampers (including TMDs) are generally classified as *passive control* devices. They consist of a mass, a spring, and a damper that are all tuned to counteract specific frequencies of vibration within a structure. In this sense, dampers do not require external power or feedback mechanisms to function; instead, they rely on the resonance between the device and the structural vibrations to dissipate energy and reduce oscillations. In contrast, active devices would use sensors, controllers, and actuators to adjust damping forces dynamically based on real-time feedback. Some TMDs can also be modified into semi-active or hybrid systems that have limited control capabilities; these can be either fully active mass dampers (AMDs) or hybrid control systems. In this sense, real-time monitoring and smart bridge (AI-powered) solutions can be used to provide the feedback required to the actuators. Such strategies can be better detailed as feedback or feedforward control, depending on whether the system responds to current vibrations (feedback control) or anticipates future conditions based on external excitations (feedforward control).

Nevertheless, these advanced SCHM systems are still exceedingly rare, even at the research level. Among the few examples found in the scientific literature, it is worth recalling the numerical simulations preferred for the Seriate footbridge [115], the design of an experimental implementation for the Valladolid Science Museum Footbridge in Spain proposed in [116], the semi-AMD-controlled experimental footbridge at the Faculty of Engineering of the University of Porto (FEUP) [117], the system deployed in a cable-stayed footbridge in Forcheim, Germany [118,119], and the magnetorheological device tested on a bridge in Volgograd, Russia [120].

## 9. Conclusions

Human–structure interaction (HSI) and structure-to-human interaction (S2HI) are two complementary points of view of a single complicated phenomenon. This is extremely relevant in the context of slender and lightweight pedestrian and cyclo-pedestrian bridges. In fact, these elegant infrastructures inherently exhibit an intricate dynamic behaviour, with larger amplitudes and low natural frequencies due to their lower stiffness and mass. Furthermore, the added mass and damping of standing or walking human bodies is proportionally significant and cannot be neglected, differently from their more massive and rigid counterparts (road and rail bridges). Therefore, human gait and bridge response influence one another in a feedback loop.

This work aimed to provide a general overview of the current state of research in these areas, providing a broad perspective that highlights key gaps and advancements. Indeed, despite the abundance of bibliographic material on some very specific research points, a comprehensive overview of the topic was lacking, especially considering the key aspects from a biomechanical point of view—i.e., from an S2HI perspective. This review aimed to fill this gap; to fulfil this objective, more than 80 relevant publications in these fields have been surveyed and selected.

The review was organised into sections that addressed the main research streams—vertical vs. lateral vibrations and single-human vs. crowd modelling. The bibliographic analysis revealed the following findings:

1. There is a greater number of studies dedicated to the investigation of vertical vibrations compared to lateral vibrations, despite the latter being critical in notable events like the Millennium Bridge incident.
2. Most research isolates vertical and lateral vibrations, whereas a coupled approach would provide a more accurate understanding.
3. Modelling predominantly emphasises single pedestrians, neglecting the complex dynamics of crowds and their collective behaviour under structural influence.
4. The effects of the human-induced effects and dynamic loads on the structure's vibrational behaviour are much more commonly addressed than the opposite—i.e., the effects of the structure dynamics on the single-human gait and the crowd behaviour.
5. The guidelines currently adopted for the construction of footbridges neglect the aspect of pedestrian comfort and adopt overly simplistic criteria for human/crowd modelling.

To summarise, over the past 20 years, especially after the Millennium Bridge incident, research has made significant progress in the field of human modelling, providing various approaches to understanding and explaining the phenomena of HSI and S2HI. However, none of these approaches are completely exhaustive. Each presents critical issues, considering, e.g., that, as previously reported, all these studies overlook the panic (or other psychological effects) that could arise in situations of discomfort.

Additionally, there is a lack of more comprehensive studies on the combined effects of vibrations, as some mechanisms of discomfort due to simultaneous multiple effects are still not well understood. For instance, based on the reviewed literature, it seems that no author has addressed the issue of combined environmental and human-induced loads, e.g., wind loads plus lateral horizontal vibrations.

Considering these aspects, especially from a new pedestrian-centred perspective, it is argued that the current guidelines need to be further improved by accounting for the results reported in the most recent studies on S2HI. Additionally, further research is needed to achieve a complete understanding of the subject. Adopting more accurate criteria for human modelling and considering pedestrian comfort can lead to safer and more comfortable footbridge designs. Finally, Structural Control and Health Monitoring systems, such as adaptive mass dampers, can effectively attenuate all these issues, addressing not only the ultimate limit state of the infrastructure but also its serviceability limit state, taking active countermeasures when the vertical and horizontal vibration amplitudes reach undesirable levels.

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## References

1. Dallard, P.; Fitzpatrick, A.J.; Flint, A.; Bourva, S.; Low, A.; Smith, R.M.; Willford, M. The London Millennium Footbridge. *Struct. Eng.* **2001**, *79*, 17–33.
2. Blekherman, A.N. Autoparametric Resonance in a Pedestrian Steel Arch Bridge: Solferino Bridge, Paris. *J. Bridge Eng.* **2007**, *12*, 669–676. [CrossRef]
3. Xiong, J.; Chen, J.; Caprani, C. Spectral Analysis of Human-Structure Interaction during Crowd Jumping. *Appl. Math. Model.* **2021**, *89*, 610–626. [CrossRef]
4. Van Nimmen, K.; Pavic, A.; Van den Broeck, P. A Simplified Method to Account for Vertical Human-Structure Interaction. *Structures* **2021**, *32*, 2004–2019. [CrossRef]
5. Ahmadi, E.; Caprani, C.; Živanović, S.; Heidarpour, A. Assessment of Human-Structure Interaction on a Lively Lightweight GFRP Footbridge. *Eng. Struct.* **2019**, *199*, 109687. [CrossRef]
6. Shahabpoor, E.; Pavic, A.; Racic, V. Interaction between Walking Humans and Structures in Vertical Direction: A Literature Review. *Shock Vib.* **2016**, *2016*, 3430285. [CrossRef]
7. Shahabpoor, E.; Pavic, A.; Racic, V. Structural Vibration Serviceability: New Design Framework Featuring Human-Structure Interaction. *Eng. Struct.* **2017**, *136*, 295–311. [CrossRef]
8. Van Nimmen, K.; Lombaert, G.; De Roeck, G.; Van den Broeck, P. Vibration serviceability of footbridges: Evaluation of the current codes of practice. *Eng. Struct.* **2014**, *59*, 448–461. [CrossRef]
9. Van Nimmen, K.; Lombaert, G.; De Roeck, G.; Van den Broeck, P. The Impact of Vertical Human-Structure Interaction on the Response of Footbridges to Pedestrian Excitation. *J. Sound Vib.* **2017**, *402*, 104–121. [CrossRef]
10. Civera, M.; Rosso, M.M.; Marano, G.C.; Chiaia, B. Validation and Comparison of Two AOMA Approaches for the Ambient Vibration Testing of Long Suspension Bridges Under Strong Wind Loads. In *International Operational Modal Analysis Conference*; Springer Nature Switzerland: Cham, Switzerland, 2024; Volume 515, pp. 475–484. [CrossRef]
11. Civera, M.; Sibille, L.; Zanotti Fragonara, L.; Ceravolo, R. A DBSCAN-Based Automated Operational Modal Analysis Algorithm for Bridge Monitoring. *Measurement* **2023**, *208*, 112451. [CrossRef]
12. Martucci, D.; Civera, M.; Surace, C. Bridge Monitoring: Application of the Extreme Function Theory for Damage Detection on the I-40 Case Study. *Eng. Struct.* **2023**, *279*, 115573. [CrossRef]
13. Casalegno, C.; Russo, S. Dynamic Characterization of an All-FRP Bridge. *Mech. Compos. Mater.* **2017**, *53*, 17–30. [CrossRef]

14. Drygala, I.J.; Dulinska, J.M.; Ciura, R.; Lachawiec, K. Vibration Serviceability of Footbridges: Classical vs. Innovative Material Solutions for Deck Slabs. *Materials* **2020**, *13*, 3009. [CrossRef] [PubMed]
15. Colmenares, D.; Costa, G.; Civera, M.; Surace, C.; Karoumi, R. Quantification of the Human–Structure Interaction Effect through Full-Scale Dynamic Testing: The Folke Bernadotte Bridge. *Structures* **2023**, *55*, 2249–2265. [CrossRef]
16. Colmenares, D.; Andersson, A.; Karoumi, R. Closed-Form Solution for Mode Superposition Analysis of Continuous Beams on Flexible Supports under Moving Harmonic Loads. *J. Sound Vib.* **2022**, *520*, 116587. [CrossRef]
17. Quqa, S.; Giordano, P.F.; Limongelli, M.P. Shared Micromobility-Driven Modal Identification of Urban Bridges. *Autom. Constr.* **2022**, *134*, 104048. [CrossRef]
18. Dallard, P.; Fitzpatrick, T.; Flint, A.; Low, A.; Smith, R.R.; Willford, M.; Roche, M. London millennium bridge: Pedestrian-induced lateral vibration. *J. Bridge Eng.* **2001**, *6*, 412–417. [CrossRef]
19. Ingólfsson, E.T.; Georgakis, C.T.; Jönsson, J. Pedestrian-induced lateral vibrations of footbridges: A literature review. *Eng. Struct.* **2012**, *45*, 21–52. [CrossRef]
20. Brownjohn, J.; Fok, P.; Roche, M.; Omenzetter, P. *Long Span Steel Pedestrian Bridge at Singapore Changi Airport—Part 1: Prediction of Vibration Serviceability Problems*; The Structural Engineer: Singapore, 2004.
21. Caetano, E.; Cunha, Á.; Magalhães, F.; Moutinho, C. Studies for Controlling Human-Induced Vibration of the Pedro e Inês Footbridge, Portugal. Part 1: Assessment of Dynamic Behaviour. *Eng. Struct.* **2010**, *32*, 1069–1081. [CrossRef]
22. Caetano, E.; Cunha, Á.; Moutinho, C.; Magalhães, F. Studies for Controlling Human-Induced Vibration of the Pedro e Inês Footbridge, Portugal. Part 2: Implementation of Tuned Mass Dampers. *Eng. Struct.* **2010**, *32*, 1082–1091. [CrossRef]
23. Fujino, Y.; Pacheco, B.M.; Nakamura, S.-I.; Warnitchai, P. Synchronization of Human Walking Observed during Lateral Vibration of a Congested Pedestrian Bridge. *Earthq. Eng. Struct. Dyn.* **1993**, *22*, 741–758. [CrossRef]
24. Nakamura, S.-I. Field Measurements of Lateral Vibration on a Pedestrian Suspension Bridge. *Struct. Eng.* **2003**, *81*, 22–26.
25. Hoorpah, W.; Flamand, O.; Cespedes, X. The Simone de Beauvoir Footbridge between Bercy Quay and Tolbiac Quay in Paris: Study and Measurement of the Dynamic Behaviour of the Structure under Pedestrian Loads and Discussion of Corrective Modifi Cations. In *Footbridge Vibration Design*; CRC Press: Boca Raton, FL, USA, 2009; pp. 111–124. [CrossRef]
26. Macdonald, J.H.G. Pedestrian-Induced Vibrations of the Clifton Suspension Bridge, UK. *Proc. Inst. Civ. Eng.-Bridge Eng.* **2008**, *161*, 69–77. [CrossRef]
27. Danion, F.; Varraine, E.; Bonnard, M.; Pailhous, J. Stride Variability in Human Gait: The Effect of Stride Frequency and Stride Length. *Gait Posture* **2003**, *18*, 69–77. [CrossRef]
28. Nilsson, J.; Thorstensson, A. Adaptability in Frequency and Amplitude of Leg Movements during Human Locomotion at Different Speeds. *Acta Physiol. Scand.* **1987**, *129*, 107–114. [CrossRef] [PubMed]
29. van der Zee, T.J.; Mundinger, E.M.; Kuo, A.D. A Biomechanics Dataset of Healthy Human Walking at Various Speeds, Step Lengths and Step Widths. *Sci. Data* **2022**, *9*, 704. [CrossRef]
30. Bachmann, H.; Ammann, W.J.; Delschl, F.; Eisenmann, J.; Floegl, I.; Hirsch, G.H.; Klein, G.K.; Lande, G.J.; Mahrenholtz, O.; Natke, H.G.; et al. *Vibration Problems in Structures Pratical Guidelines*; Birkhauser Verlag: Zurich, Switzerland, 1995.
31. Živanović, S.; Pavic, A.; Reynolds, P. Vibration Serviceability of Footbridges under Human-Induced Excitation: A Literature Review. *J. Sound Vib.* **2005**, *279*, 1–74. [CrossRef]
32. Forner Cordero, A. *Human Gait, Stumble and…Fall? Mechanical Limitations of the Recovery from a Stumble*; University of Twente: Enshede, The Netherlands, 2003.
33. McRobie, A.; Morgenthal, G.; Lasenby, J.; Ringer, M. Section Model Tests on Human—Structure Lock-In. *Proc. Inst. Civ. Eng.-Bridge Eng.* **2003**, *156*, 71–79. [CrossRef]
34. Newland, D.E. Pedestrian Excitation of Bridges. *J. Mech. Eng. Sci.* **2004**, *2018*, 477–492. [CrossRef]
35. Racic, V.; Pavic, A.; Brownjohn, J.M.W. Experimental identification and analytical modelling of human walking forces: Literature review. *J. Sound Vib.* **2009**, *326*, 1–49. [CrossRef]
36. Wang, H. *Structural Vibration Serviceability and Human Comfort*; MDPI—Multidisciplinary Digital Publishing Institute: Basel, Switzerland, 2023; ISBN 978-3-0365-8706-6.
37. Ma, R.; Ke, L.; Wang, D.; Chen, A.; Pan, Z. Experimental Study on Pedestrians' Perception of Human-Induced Vibrations of Footbridges. *Int. J. Struct. Stab. Dyn.* **2018**, *18*, 1850116. [CrossRef]
38. Archbold, P.J. *Novel Interactive Load Models for Pedestrian Footbridges*; Faculty of Engineering and Architecture, National University of Ireland, University College Dublin: Dublin, Ireland, 2004.
39. Butz, C.; Caetano, E.; Chabrolin, B.; Cunha, A.; Goldack, A.; Keil, A.; Lemaire, A.; Lukić, M.; Martin, P.-O.; Schlaich, M.; et al. *Design of Lightweight Footbridges for Human Induced Vibrations*; Publications Office of the European Union: Luxembourg, 2009; Volume 82. [CrossRef]
40. Blanchard, J.; Davies, B.L.; Smith, J.W. *Design Criteria and Analysis for Dynamic Loading of Test Bridges. Proceedings of a Symposium on Dynamic Behaviour of Bridges*; Transport and Road Research Laboratory (TRRL): Crowthorne, UK, 1977.

41. Leonard, D. *Human Tolerance Limits for Bridge Vibrations. Transport and Road Research Laboratory Supplementary Report 34*; Road Research Laboratory: Wokingham, UK, 1966.
42. Smith, J. *The Vibration of Highway Bridges and the Effects on Human Comfort*; The University of Bristol: Bristol, UK, 1969.
43. Fanning, P.J.; Healy, P.; Pavic, A. Pedestrian Bridge Vibraiton Serviceability—A Case Study in Testing and Simulation. *Adv. Struct. Eng.* **2010**, *13*, 861–873. [CrossRef]
44. Venuti, F.; Racic, V.; Corbetta, A. Modelling Framework for Dynamic Interaction between Multiple Pedestrians and Vertical Vibrations of Footbridges. *J. Sound Vib.* **2016**, *379*, 245–263. [CrossRef]
45. Živanović, S. Benchmark Footbridge for Vibration Serviceability Assessment under the Vertical Component of Pedestrian Load. *J. Struct. Eng.* **2012**, *138*, 1193–1202. [CrossRef]
46. Macdonald, J.H.G. Lateral Excitation of Bridges by Balancing Pedestrians. *Proc. R. Soc. A Math. Phys. Eng. Sci.* **2009**, *465*, 1055–1073. [CrossRef]
47. Brady, R.A.; Peters, B.T.; Bloomberg, J.J. Strategies of Healthy Adults Walking on a Laterally Oscillating Treadmill. *Gait Posture* **2009**, *29*, 645–649. [CrossRef]
48. Stokes, H.E.; Thompson, J.D.; Franz, J.R. The Neuromuscular Origins of Kinematic Variability during Perturbed Walking. *Sci. Rep.* **2017**, *7*, 808. [CrossRef] [PubMed]
49. Wolfson, L.I.; Whipple, R.; Amerman, P.; Kaplan, J.; Kleinberg, A. Gait and Balance in the Elderly: Two Functional Capacities That Link Sensory and Motor Ability to Falls. *Clin. Geriatr. Med.* **1985**, *1*, 649–659. [CrossRef]
50. Bocian, M.; Brownjohn, J.M.W.; Racic, V.; Hester, D.; Quattrone, A.; Monnickendam, R. A Framework for Experimental Determination of Localised Vertical Pedestrian Forces on Full-Scale Structures Using Wireless Attitude and Heading Reference Systems. *J. Sound Vib.* **2016**, *376*, 217–243. [CrossRef]
51. Harle, R. A Survey of Indoor Inertial Positioning Systems for Pedestrians. *IEEE Commun. Surv. Tutor.* **2013**, *15*, 1281–1293. [CrossRef]
52. Aux, J.D.; Castillo, B.; Marulanda, J.; Thomson, P. Modelling Human-Structure Interaction in Pedestrian Bridges Using a Three-Dimensional Biomechanical Approach. *Appl. Sci.* **2024**, *14*, 7257. [CrossRef]
53. Guignard, J.C. Human Sensitivity to Vibration. *J. Sound Vib.* **1971**, *15*, 11–16. [CrossRef]
54. Thuong, O.; Griffin, M.J. The Vibration Discomfort of Standing People: Evaluation of Multi-Axis Vibration. *Ergonomics* **2015**, *58*, 1647–1659. [CrossRef] [PubMed]
55. Castillo, B.; Marulanda, J.; Thomson, P. Innovative Experimental Assessment of Human–Structure Interaction Effects on Footbridges with Accurate Multi-Axial Dynamic Sensitivity Using Real-Time Hybrid Simulation. *Appl. Sci.* **2024**, *14*, 8908. [CrossRef]
56. Griffin, M.L. *Handbook of Human Vibration*; Academic Press: Southampton, UK; Human Factors Research Unit, Institute of Sound and Vibration Research, The University: Southampton, UK, 1990.
57. Matsumoto, Y.; Griffin, M.J. Dynamic Response of the Standing Human Body Exposed to Vertical Vibration: Influence of Posture and Vibration Magnitude. *J. Sound Vib.* **1998**, *212*, 85–107. [CrossRef]
58. Kiiski, J.; Heinonen, A.; Järvinen, T.L.; Kannus, P.; Sievänen, H. Transmission of Vertical Whole Body Vibration to the Human Body. *J. Bone Miner. Res.* **2008**, *23*, 1318–1325. [CrossRef] [PubMed]
59. Pollock, R.D.; Woledge, R.C.; Mills, K.R.; Martin, F.C.; Newham, D.J. Muscle Activity and Acceleration during Whole Body Vibration: Effect of Frequency and Amplitude. *Clin. Biomech.* **2010**, *25*, 840–846. [CrossRef] [PubMed]
60. Gheitasi, A.; Ozbulut, O.E.; Usmani, S.; Alipour, M.; Harris, D.K. Experimental and Analytical Vibration Serviceability Assessment of an In-Service Footbridge. *Case Stud. Nondestruct. Test. Eval.* **2016**, *6*, 79–88. [CrossRef]
61. Huang, Y.; Zhang, P. Subjective Discomfort Caused by Vertical Whole-Body Vibration in the Frequency Range 2–100 Hz. *Ergonomics* **2019**, *62*, 420–430. [CrossRef]
62. Castillo, B.; Marulanda, J.; Thomson, P. Experimental Evaluation of Pedestrian-Induced Multiaxial Gait Loads on Footbridges: Effects of the Structure-to-Human Interaction by Lateral Vibrating Platforms. *Sensors* **2024**, *24*, 2517. [CrossRef]
63. Baker, W.D.R.; Mansfield, N.J. Effects of Horizontal Whole-Body Vibration and Standing Posture on Activity Interference. *Ergonomics* **2010**, *53*, 365–374. [CrossRef] [PubMed]
64. Cuevas, R.G.; Jiménez-Alonso, J.F.; Martínez, F.; Díaz, I.M. Uncertainty-Based Approaches for the Lateral Vibration Serviceability Assessment of Slender Footbridges. *Structures* **2021**, *33*, 3475–3485. [CrossRef]
65. Dang, H.V.; Živanović, S. Experimental Characterisation of Walking Locomotion on Rigid Level Surfaces Using Motion Capture System. *Eng. Struct.* **2015**, *91*, 141–154. [CrossRef]
66. *ISO 18649:2004*; Mechanical Vibration-Evaluation of Measurement Results from Dynamic Tests and Investigations on Bridges Vibrations Mécaniques-Évaluation Des Résultats de Mesures Relatives Aux Essais Dynamiques et Aux Investigations Sur Les, Ponts. Technical Committee ISO/TC 108, Mechanical Vibration and Shock; ISO: Geneve, Switzerland, 2004.

67. Butz, C.; Heinemeyer, C.; Keil, A.; Schlaich, M.; Goldack, A.; Trometer, S.; Lukić, M.; Chabrolin, B.; Lemaire, A.; Martin, P.-O.; et al. Design of Footbridges Guideline (RFS2-CT-2007-00033). 2008. Available online: https://www.stahlbau.stb.rwth-aachen.de/projekte/2007/HIVOSS/docs/Footbridge_Guidelines_EN03.pdf (accessed on 1 December 2024).
68. Caprani, C.C.; Ahmadi, E. Formulation of Human–Structure Interaction System Models for Vertical Vibration. *J. Sound Vib.* **2016**, *377*, 346–367. [CrossRef]
69. *EN 1995-2*; Eurocode 5: Design of Timber Structures—Part 2: Bridges. European Committee for Standardization: Brussels, Belgium, 2004.
70. British Standards Institution. *Steel, Concrete and Composite Bridges. Code of Practice for Design of Steel Bridges*; British Standards Institution: London, UK, 2000; ISBN 0580330648.
71. Technical Committee CEN/TC 250. *EN 1991-2 Eurocode 1: Actions on Structures—Part 2: Traffic Loads on Bridges*; European Committee for Standardization: Brussels, Belgium, 2003.
72. Biggs, J.M. *Introduction to Structural Dynamics*; McGraw-Hill College: New York, NY, USA, 1964.
73. O'Sullivan, D.; Caprani, C.; Keogh, J. The Response of a Footbridge to Pedestrians Carrying Additional Mass. In Proceedings of the BCRI (Bridge and Concrete Research Ireland) Conference, Dublin, Ireland, 6–7 September 2012. [CrossRef]
74. Shahabpoor, E.; Pavic, A.; Racic, V. Identification of Mass-Spring-Damper Model of Walking Humans. *Structures* **2016**, *5*, 233–246. [CrossRef]
75. da Silva, F.T.; Brito, H.M.B.F.; Pimentel, R.L. Modeling of Crowd Load in Vertical Direction Using Biodynamic Model for Pedestrians Crossing Footbridges. *Can. J. Civ. Eng.* **2013**, *40*, 1196–1204. [CrossRef]
76. de Roeck, G. *EURODYN 2011: 8th International Conference on Structural Dynamics: Leuven, Belgium, 4–6 July 2011*; Katholieke Universiteit Leuven; European Association of Structural Dynamics: Leuven, Belgium, 2011; ISBN 9789076019314.
77. Brownjohn, J.M.W.; Pavic, A.; Omenzetter, P. A Spectral Density Approach for Modelling Continuous Vertical Forces on Pedestrian Structures Due to Walking. *Can. J. Civ. Eng.* **2004**, *31*, 65–77. [CrossRef]
78. De Roeck, G.; Katholieke Universiteit Leuven. EURODYN (8 2011.07.04-06 Leuven); International Conference on Structural Dynamics (8 2011.07.04-06 Leuven). In Proceedings of the 8th International Conference on Structural Dynamics, EURODYN 2011, Leuven, Belgium, 4–6 July 2011; ISBN 9789076019314.
79. Belykh, I.; Jeter, R.; Belykh, V. Foot Force Models of Crowd Dynamics on a Wobbly Bridge. *Sci. Adv.* **2017**, *3*, e1701512. [CrossRef]
80. Zhao, H.; Zhang, L.; Qiu, S.; Wang, Z.; Yang, N.; Xu, J. Pedestrian Dead Reckoning Using Pocket-Worn Smartphone. *IEEE Access* **2019**, *7*, 91063–91073. [CrossRef]
81. Zhang, Q.; Chen, W. A Bipedal Walking Model Considering Trunk Pitch Angle for Estimating the Influence of Suspension Load on Human Biomechanics. *IEEE Trans. Biomed. Eng.* **2024**, 1–11. [CrossRef] [PubMed]
82. Qin, J.W.; Law, S.S.; Yang, Q.S.; Yang, N. Pedestrian-Bridge Dynamic Interaction, Including Human Participation. *J. Sound Vib.* **2013**, *332*, 1107–1124. [CrossRef]
83. Geyer, H.; Seyfarth, A.; Blickhan, R. Compliant Leg Behaviour Explains Basic Dynamics of Walking and Running. *Proc. R. Soc. B Biol. Sci.* **2006**, *273*, 2861–2867. [CrossRef] [PubMed]
84. Aux, J.D.; Castillo, B.; Riascos, C.; Marulanda, J.; Thomson, P. Evaluation of Vertical Human-Structure Interaction on a Pedestrian Bridge Using a Predictive Human Gait Model. *Struct. Control. Health Monit.* **2024**, *1*, 8880701. [CrossRef]
85. Kim, S.-H.; Cho, K.-I.; Choi, M.-S.; Lim, J.-Y. Development of Human Body Model for the Dynamic Analysis of Footbridges under Pedestrian Induced Excitation. *Steel Struct.* **2008**, *8*, 333–345.
86. Ricciardelli, F.; Asce, M.; Pizzimenti, A.D. Lateral Walking-Induced Forces on Footbridges. *J. Bridge Eng.* **2007**, *12*, 677–688. [CrossRef]
87. Han, H.; Zhou, D.; Ji, T.; Zhang, J. Modelling of Lateral Forces Generated by Pedestrians Walking across Footbridges. *Appl. Math. Model.* **2021**, *89*, 1775–1791. [CrossRef]
88. Strogatz, S.H.; Abrams, D.M.; McRobie, A.; Eckhardt, B.; Ott, E. Theoretical Mechanics: Crowd Synchrony on the Millennium Bridge. *Nature* **2005**, *438*, 43–44. [CrossRef]
89. Xie, W.; Hua, Y. Structural Vibration Comfort: A Review of Recent Developments. *Buildings* **2024**, *14*, 1592. [CrossRef]
90. Beltaief, O.; El Hadouaj, S.; Ghedira, K. Multi-Agent Simulation Model of Pedestrians Crowd Based on Psychological Theories. In Proceedings of the 2011 4th International Conference on Logistics, Hammamet, Tunisia, 31 May–3 June 2011.
91. Challenger, R. *Emergency Planning College Understanding Crowd Behaviours: Guidance and Lessons Identified*; University of Leeds: Leeds, UK, 2009; ISBN 9781874321200.
92. Alsaleh, R.; Sayed, T. Markov-Game Modeling of Cyclist-Pedestrian Interactions in Shared Spaces: A Multi-Agent Adversarial Inverse Reinforcement Learning Approach. *Transp. Res. Part C Emerg. Technol.* **2021**, *128*, 103191. [CrossRef]
93. Smirnov, E.; Dunaenko, S.; Kudinov, S. Using Multi-Agent Simulation to Predict Natural Crossing Points for Pedestrians and Choose Locations for Mid-Block Crosswalks. *Geo-Spat. Inf. Sci.* **2020**, *23*, 362–374. [CrossRef]
94. Kimura, T.; Sano, T.; Hayashida, K.; Takeichi, N.; Minegishi, Y.; Yoshida, Y.; Watanabe, H. Representation of Crowd in Multi-Agent Model. *J. Archit. Plan.* **2009**, *74*, 371–377. [CrossRef]

95. Belykh, I.; Bocian, M.; Champneys, A.R.; Daley, K.; Jeter, R.; Macdonald, J.H.G.; McRobie, A. Emergence of the London Millennium Bridge Instability without Synchronisation. *Nat. Commun.* **2021**, *12*, 7223. [CrossRef] [PubMed]
96. Venuti, F.; Bruno, L.; Bellomo, N. Crowd Dynamics on a Moving Platform: Mathematical Modelling and Application to Lively Footbridges. *Math. Comput. Model.* **2007**, *45*, 252–269. [CrossRef]
97. Carroll, S.P.; Owen, J.S.; Hussein, M.F.M. A Coupled Biomechanical/Discrete Element Crowd Model of Crowd-Bridge Dynamic Interaction and Application to the Clifton Suspension Bridge. *Eng. Struct.* **2013**, *49*, 58–75. [CrossRef]
98. Helbing, D.; Molnar, P. Social Force Model for Pedestrian Dynamics. *Phys. Rev. E* **1995**, *51*, 4282. [CrossRef] [PubMed]
99. Jiménez-Alonso, J.F.; Sáez, A. Recent Advances in the Serviceability Assessment of Footbridges Under Pedestrian-Induced Vibrations. *Bridge Eng.* **2018**, *61*. [CrossRef]
100. Carroll, S.P.; Owen, J.S.; Hussein, M.F.M. Modelling Crowd-Bridge Dynamic Interaction with a Discretely Defined Crowd. *J. Sound Vib.* **2012**, *331*, 2685–2709. [CrossRef]
101. Venuti, F.; Tubino, F. Human-Induced Loading and Dynamic Response of Footbridges in the Vertical Direction Due to Restricted Pedestrian Traffic. *Struct. Infrastruct. Eng.* **2021**, *17*, 1431–1445. [CrossRef]
102. Fruin, J.J. *Designing for Pedestrians: A Level-of-Service Concept*; The Port of New York Authority: New York, NY, USA, 1970.
103. Weidmann, U. Transporttechnik Der Fussgänger Transporttechnische Eigenschaften Des Fussgängerverkehrs, Literaturauswertung. *IVT Schriftenreihe* **1993**, *90*. [CrossRef]
104. Tanaboriboon, Y.; Siang Hwa, S.; Chor, C.H. Pedestrian Characteristics Study in Singapore. *J. Transp. Eng.* **1986**, *112*, 229–235. [CrossRef]
105. Virkler, M.R.; Elayadath, S. *Research Issues on Bicycling, Pedestrians, and Older Drivers, Transportation Research Record No. 1438*; National Academy Press: Washington, DC, USA, 1994.
106. Li, Q.; Fan, J.; Nie, J.; Li, Q.; Chen, Y. Crowd-Induced Random Vibration of Footbridge and Vibration Control Using Multiple Tuned Mass Dampers. *J. Sound Vib.* **2010**, *329*, 4068–4092. [CrossRef]
107. Helbing, D.; Farkas, I.; Vicsek, T. Simulating dynamical features of escape panic. *Nature* **2000**, *407*, 487–490. [CrossRef] [PubMed]
108. Hu, W.H.; Moutinho, C.; Caetano, E.; Magalhes, F.; Cunha, L. Continuous Dynamic Monitoring of a Lively Footbridge for Serviceability Assessment and Damage Detection. *Mech. Syst. Signal Process.* **2012**, *33*, 38–55. [CrossRef]
109. Moser, P.; Moaveni, B. Environmental Effects on the Identified Natural Frequencies of the Dowling Hall Footbridge. *Mech. Syst. Signal Process.* **2011**, *25*, 2336–2357. [CrossRef]
110. Van Nimmen, K.; Van Hauwermeiren, J.; Van den Broeck, P. Eeklo Footbridge: Benchmark Dataset on Pedestrian-Induced Vibrations. *J. Bridge Eng.* **2021**, *26*. [CrossRef]
111. Steinman, D.B. Modes and Natural Frequencies of Suspension Bridge Oscillations. *J. Frankl. Inst.* **1959**, *268*, 148–174. [CrossRef]
112. Pavic, A.; Willford, M.; Reynolds, P.; Wright, J. Key Results of Modal Testing of The Millennium Bridge, London. *Proc. Footbridge* **2002**, *2002*, 1–10.
113. Pavia, A.; Zivanovic, S. Probabilistic Assessment of Human Response to Footbridge Vibration. *J. Low. Freq. Noise Vib. Act. Control* **2009**, *28*, 255–268. [CrossRef]
114. Saeed, M.U.; Sun, Z.; Elias, S. Research Developments in Adaptive Intelligent Vibration Control of Smart Civil Structures. *J. Low. Freq. Noise Vib. Act. Control* **2022**, *41*, 292–329. [CrossRef]
115. Preumont, A.; Voltan, M.; Sangiovanni, A.; Bastaits, R.; Mokrani, B.; Alaluf, D. An Investigation of the Active Damping of Suspension Bridges. *Math. Mech. Complex. Syst.* **2015**, *3*, 385–406. [CrossRef]
116. Casado, C.M.; Díaz, I.M.; de Sebastián, J.; Poncela, A.V.; Lorenzana, A. Implementation of Passive and Active Vibration Control on an In-Service Footbridge. *Struct. Control Health Monit.* **2013**, *20*, 70–87. [CrossRef]
117. Moutinho, C.; Cunha, Á.; Caetano, E.; de Carvalho, J.M. Vibration Control of a Slender Footbridge Using Passive and Semiactive Tuned Mass Dampers. *Struct. Control Health Monit.* **2018**, *25*, e2208. [CrossRef]
118. Occhiuzzi, A.; Spizzuoco, M.; Serino, G. Semi-Active MR Dampers in TMD's for Vibration Control of Footbridges, Part 1: Numerical Modeling and Control Algorithm. In Proceedings of the Conference Footbridge 2002, Paris, France, 20–22 November 2002.
119. Seiler, G.; Fischer, O.; Huber, P. Semi-Active MR Dampers in TMD's for Vibration Control of Footbridges, Part 2: Numerical Analysis and Practical Realisation. In Proceedings of the Conference Footbridge 2002, Paris, France, 20–22 November 2002.
120. Weber, F.; Maślanka, M. Frequency and Damping Adaptation of a TMD with Controlled MR Damper. *Smart Mater. Struct.* **2012**, *21*, 055011. [CrossRef]