vibration

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Systematic Review

Vibration Transmission during Manual Wheelchair Propulsion: A Systematic Review

Ophélie Lariviere [1,2,*], Delphine Chadefaux [1,2], Christophe Sauret [3,4] and Patricia Thoreux [1,5]

[1] Institut de Biomécanique Humaine Georges Charpak, IBHGC, Université Sorbonne Paris Nord, UR 4494, F-93000 Bobigny, France; delphine.chadefaux@sorbonne-paris-nord.fr (D.C.); patricia.thoreux@aphp.fr (P.T.)
[2] Département STAPS, Université Sorbonne Paris Nord, F-93000 Bobigny, France
[3] Arts et Métiers Institute of Technology, Institut de Biomécanique Humaine Georges Charpak, IBHGC, UR 4494, F-75013 Paris, France; christophe.sauret@invalides.fr
[4] Centre d'Etudes et de Recherchesur l'Appareillage des Handicapés, Institution Nationale des Invalides, F-94000 Créteil, France
[5] Hôpital Hôtel Dieu, AP-HP, F-75004 Paris, France
* Correspondence: ophelie.lariviere@sorbonne-paris-nord.fr

Abstract: Manual wheelchair (MWC) propulsion can expose the user to significant vibration. Human body exposure to certain vibrations can be detrimental to health, and a source of discomfort and fatigue. Therefore, identifying vibration exposure and key parameters influencing vibration transmissibility during MWC propulsion is crucial to protect MWC users from vibration risks. For that purpose, a systematic review using PRISMA recommendations was realized to synthesize the current knowledge regarding vibration transmissibility during MWC propulsion. The 35 retrieved articles were classified into three groups: Vibration content, parameters influencing vibration transmission, and vibration transmission modeling. The review highlighted that MWC users experience vibration in the frequency range detrimental/uncomfortable for human vibration transmission during MWC propulsion depends on many parameters and is still scarcely studied and understood. A modeling and simulation approach would be an interesting way to assist physicians in selecting the best settings for a specific user, but many works (modeling, properties identification, etc.) must be done before being effective for clinical and industrial purposes.

Keywords: whole-body vibration; manual wheelchair; health; modeling

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1. Introduction

The human body is regularly exposed to vibration during transport, work, or sports activities. Vibration exposure is usually characterized by the exposure time, and by vibration frequency and amplitude. While positive effects of vibration exposure have been reported, to treat osteoporosis [1] and to increase strength and power in the lower limb muscles [2], for instance, vibration exposure is also assumed to cause deleterious effects on human body integrity [3]. Epidemiological studies on truck drivers demonstrated that daily exposure to vibration could increase the risks of developing prostate cancer [4] and cardiovascular diseases [5]. Other articles reported that workers exposed daily to whole-body vibration, such as bus and truck drivers, are more prone to suffer from lower back [6,7] and neck pains [8]. These pains could be explained by a deterioration of intervertebral discs; which was observed by Dupuis and Zerlett on the lumbar spine of earth-moving machine workers [3]. Articles also indicated that vibrations induce discomfort and are associated with an increase in reaction time [9] and alterations of both vision and balance [10–14]. Other physiological effects, such as headaches and digestive disorders, have also been reported by people exposed to whole-body vibration (WBV) [13,15]. Lastly, other articles have shown that vibration exposure increases muscular and psychological fatigue [16,17].

The comparison of the articles highlighting either detrimental or beneficial effects of vibration exposure revealed that the vibration characteristics differed in terms of frequency, and duration of exposure. Truck drivers are exposed to vibration resulting in amplitude up to 4 m/s^2 in a frequency range below 20 Hz during 8 to 12 h per day [13]. Similar values were observed on a riding cyclist [18]. However, in the case of osteoporosis treatment, people are exposed to vibration with similar amplitude (3–10 m/s^2), but with both higher frequencies (30–40 Hz) and shorter exposure time (less than one hour per week distributed in 15 min sessions) [19].

Under this framework, guidelines were developed for workers' health protection. European directive 2002/44/EC [20] and the International Standard Organization (ISO), through ISO-2636-1 (mechanical vibration and shock, evaluation of human exposure to whole-body vibration) [21], weighted the acceleration measured at the interface between the vibrating structure and the human to give higher importance to frequencies deleterious for the human body. Based on the weighted acceleration, two parameters were defined: The effective value of the weighted acceleration (w-RMS, unit: m/s^2) and the vibration dose value (VDV, unit: m/s$^{1.75}$). The second parameter, VDV being more sensitive to the acceleration peaks, is recommended to estimate the amount of vibration for the case of inherent shock exposure [21]. Based on an eight-hour of exposure, a limit was defined at 1.15 m/s^2 for w-RMS and 21 m/s$^{1.75}$ for VDV, above which workers should no longer perform their tasks until means have been put in place to reduce exposure to vibration. For an exposure value lower than the exposure limit, but higher than an action level value (i.e., w-RMS = 0.5 m/s^2 and VDV = 9.1 m/s$^{1.75}$ for an eight-hour of exposure), people are still allowed to work, but with a plan to reduce vibration exposure to a level below the action level value. To reduce vibration exposure, for example, protection equipment can be set up, or a decrease of the daily exposure time may be planned. However, VDV and w-RMS parameters do not consider the interaction with the human body (i.e., effect of the muscular control, or tissue properties) [22–24]. Consequently, other parameters, such as transmissibility, have also been proposed in the literature.

In addition to these guidelines, various mathematical models of the human body were developed to predict the amount of vibration and identify parameters that could decrease vibration exposure. Among the different models, the models based upon lumped parameters are the most common for predicting WBV transmission [22]. These models are based on the transfer function between different points of the human body and are composed of mass, springs, and dampers. Many lumped models were developed to represent people seated on a dynamic seat [25]. The drawback of these models is that they are often developed to describe a unidirectional dynamic response, and they are not consistent with the human properties (anthropometry and joints' degrees of freedom) [10,26]. Therefore, finite element models [27] were recently proposed. This model provides a good representation of the human body. However, they need a high computational cost. Conversely, regression models based on a neural network [28] are accurate without a high computational cost. However, such models did not represent the human body. Therefore, a compromise could be the multibody models considering body non-linearities without a high computational cost [10,11,26,29].

In that respect, guidelines and models were developed in the work field to protect the human body from vibration exposure. However, such guidelines do not consider the vibration exposure in everyday life. Especially, manual wheelchair (MWC) users, using their MWC, are particularly exposed to vibration in their everyday life. Such exposition could explain some MWC users' comorbidities, such as lower back pain [30], for instance. Besides, vibration exposure also increases the rate of fatigue [31]. Hence, vibration exposure could limit the functional activity and community participation of MWC users. However, the direct application of results and standards based on healthy people to MWC users is questionable. The pathologies and hand propulsion strategies of MWC users may influence vibration transmission through the body, due to specific muscular control and posture. Moreover, reducing the daily duration of MWC use is not feasible since the MWC is the sole means of transport. Hence, studies about vibration exposure and transmission through the body, specific to MWC users, are relevant. This is all the more important as, despite the existence of the ISO 16840-2:2014 standard [32] related to shock absorption of the wheelchair seat cushion, MWC users are still suffering from lower back and neck pain [8,30].

While a large number of articles focusing on vibration exposure/transmission in the seated able-bodied human currently exists, the differences between able-bodied participants and MWC users may not transfer the results from this literature to the MWC user population. Therefore, this article aimed to establish the current state of knowledge regarding vibration exposure and the effect of its transmission from the wheelchair to the user. Through a systematic review of the literature based on PRISMA recommendations, this article synthesizes the current knowledge of vibration transmission during MWC propulsion.

2. Materials and Methods

2.1. Search Strategy

A systematic search, based on the methodology of Harris et al. [33] and Moher et al. [34], was performed to identify articles studying vibration transmission during MWC propulsion. PubMed, Scopus, Science Direct, and IEEE Xplore databases were searched for relevant articles. The request, launched in June 2020, was the following: Wheelchair AND (Vibration* OR Acceleration OR Shock* OR Modal analysis OR Dynamical analysis*).

2.2. Article Selection

Articles were selected according to the flow diagram recommended by PRISMA [33–35]. After removing duplicates, all titles were screened, and articles were selected with respect to inclusion/exclusion criteria. The inclusion criterion was all articles dealing with vibration transmission during MWC propulsion. Exclusion criteria were:Articles about other propulsion systems than handrim propulsion, car MWC restraint system, friction of MWC casters, and article not written in English. Then, all remaining abstracts and articles were finally read. The selected articles were divided into three categories depending on their topic: Vibration contents; parameters affecting vibration transmission; and modeling of vibration transmission.

3. Results

3.1. Generality

The initial search returned 657 articles. Removing duplicates resulted in 423 remaining articles. After excluding articles based on the exclusion criteria, 35 articles were finally selected and considered for review. This approach is summarized in Appendix A.

The 35 articles considered populations between one and thirty-seven participants, including able-bodied (AB) participants; spinal cord injured (SCI) participants; participants suffering from multiple sclerosis, spina bifida, or lower extremity amputation; or dummy. AB and SCI participants were investigated in 16 and 14 articles, respectively. Vibration exposure had various origins based on the MWC propulsion: Over the ground in real daily-life conditions (2 articles), on different specific floor types (7 articles), over a simulated road course which is a standardized course reproducing in a limited duration several classical real-life (10 articles), or on a treadmill (1 article). The vibration and shock exposure can also be produced by a vibrating platform (3 articles), an indenter drop (4 articles), or a drum shock simulator (rotating drum with a small metal rod fixed along the drum length) (4 articles). Vibration exposure was quantified through accelerometers measurements (34 articles), but measurement points were varied: On the seat (26 articles), on the backrest (3 articles), on the footrest (7 articles), on the MWC frame (10 articles), and/or on the participant's head (helmet or bite bar) (9 articles). Most of the articles used 3D accelerometers (28 articles) to investigate the vibration exposure in 3D (6 articles), along the anteroposterior and vertical direction (12 articles), or the vertical direction only (8 articles). Regarding the frequency domain, except for two articles, vibration exposure was mostly investigated below 120 Hz (i.e., human body frequency range). The sampling rate varied from 60 to 3750 Hz: Specifically at 60 Hz (1 article), 100 Hz (1 article), 200 Hz (10 articles), 500 Hz (3 articles), 960 Hz (1 article), 1000 Hz (5 articles), 2000 Hz (6 articles), 3200 Hz (1 article), or 3750 Hz (1 article). Most papers studied vibration exposure during propulsion at the speed of daily life (i.e., 0.8–1.2 m/s^2), and only two papers observed it at speeds equivalent to those observed during MWC sports (2.5–2.8 m/s^2 [36,37]). Articles that controlled input vibration observed various vibration properties. Input frequency was up to 15, 100, and 250 Hz for the work by authors of [30,38,39], respectively, while the amplitude varied from 0.4 to 2 m/s^2, around 0.1 m/s^2 and up to 0.4 m/s^2.

To describe vibration exposure, a set of parameters was commonly derived from the acceleration signal. The acceleration signal could be processed in the time domain (t-Acc), in the frequency domain (f-Acc), or be frequency-weighted in the time domain (w-Acc). Calculation of the w-Accis presented at equation B1 in Appendix B. Parameters of interest are defined as presented in Table 1 and Figure 1.

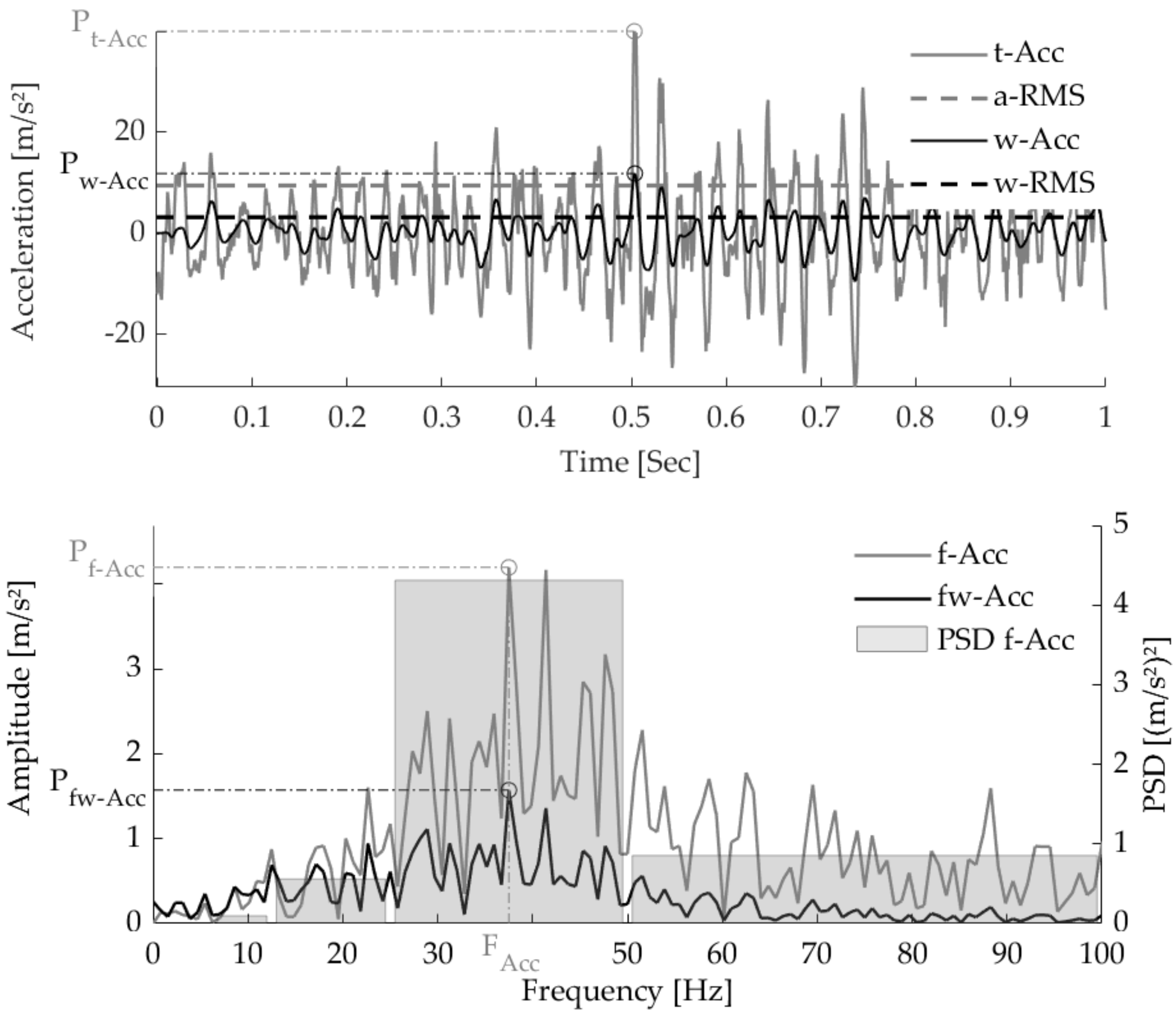

Figure 1. Representation of an acceleration signal in both time and frequency domains and the different parameters extracted in the articles were t-Acc, w-Acc are the acceleration and frequencies pondered signal in the time domain, f-Acc, fw-Acc are the acceleration and frequencies pondered spectrum and $P_{t\text{-}Acc}$, $P_{w\text{-}Acc}$, $P_{f\text{-}Acc}$, $P_{fw\text{-}Acc}$ are peak level of each signal, respectively. A-RMS and w-RMS are the mean level of t-Acc and w-Acc, respectively. PSD F_{Acc} is the power spectral density of the f-Acc.

Table 1. Parameters of interest reported for vibration exposure during MWC propulsion.

Parameters	Symbol	Unit	Nature	Formula	Interpretation
Maximum value of the acceleration in time domain	P_{t-Acc}	m/s^2	Scalar	/	Peak level of vibration
Maximum value of the frequency weighted acceleration in time domain	P_{w-Acc}	m/s^2	Scalar	/	Peak level of vibration
Maximum value of the acceleration spectrum	P_{f-Acc}	m/s^2	Scalar	/	Peak level of vibration
Root mean square of the t-Acc	a-RMS	m/s^2	Scalar	$\left[\frac{1}{T}\int_0^T Acc(t)^2\right]^{\frac{1}{2}}$	Mean level of vibration over the time of exposure (T)
Root mean square value of the w-Acc	w-RMS	m/s^2	Scalar	$\left[\frac{1}{T}\int_0^T w{-}Acc(t)^2\right]^{\frac{1}{2}}$	Mean level of vibration over the time of exposure (T)
Vibration dose value	VDV	$m^2/s^{1.75}$	Scalar	$\left[\int_0^T w{-}Acc(t)^4\right]^{\frac{1}{4}}$	Mean level of vibration over the time of exposure (T) taking more importance on high value
Power spectral density per octave	PSD	$m^2.s^{-4}/Hz$	Scalars	$\frac{1}{f_2-f_1}\lvert spectrum(Acc)\rvert^2$	Energy for each band of frequency from the frequency f1 to f2
Vibration transmissibility of t-Acc or f-Acc maximum, w-Acc maximum, a-RMS or VDV between two point of measure	T_{t-Acc} T_{f-Acc} T_{w-Acc} T_{a-RMS} T_{VDV}	None	Scalar	$T_{VDV} = \frac{VDV_{seat}}{VDV_{footrest}}$	A transmissibility superior to one means that the amount of vibration was amplified. Lower to one the vibration is damped by the system
Transfer function	H	None	Vector	$\frac{Spectrum(Acc_i)\times Spectrum(Acc_o)^*}{Spectrum(Acc_i)\times Spectrum(Acc_i)^*}$	Transmissibility between input (Acci) and output (Acco) measurement in the frequency domain; * is the conjugate value.
Eigenfrequency	f	Hz	Scalars	Peaks and phase change over transfer functions between different points of a system	Frequencies at which a system tends to oscillate in absence of forces

The results of this review are presented below, according to the three following themes: Description of the vibration content reaching the human body; parameters influencing vibration transmissibility; and modeling of vibration through MWC and/or MWC users. These three themes refer to 27, 29, and 6 articles, respectively.

3.2. Vibration Content Reaching the Human Body

Twenty-seven papers focused on describing the vibration content at which the human body is exposed during MWC propulsion. Results were presented under five subcategories: Vibration direction (5 articles), amount of vibration (14 articles), vibration frequencies (12 articles), vibration transmissibility (6 articles), and pathologies related to vibration exposure (3 articles).

3.2.1. Vibration Direction

Five articles studied vibration direction during MWC propulsion. One article considered the MWC only. For the other articles, the number of participants ranged from 10 to 33, and the studied population were AB (2 articles), or MWC users (3 articles). Data were acquired during real daily-life propulsion (1 article), over a simulated road course (3 articles), or on a treadmill (1 article). Accelerometers were placed on the seat (4 articles), on the MWC frame (2 articles), and/or on the participant's head (2 articles). Acceleration was observed along the three directions (3 articles), along the anteroposterior and vertical directions (2 articles), and for frequency sampling above 100 Hz. Parameters studied were w-RMS (1 article), VDV (1 article), T_{VDV} (3 articles), PSD (1 article), or users feeling through a survey (1 article).

All articles reported that the acceleration during MWC propulsion was preponderantly in the vertical direction, compared to the mediolateral component (see Table 2). For instance, during propulsion on a treadmill, Waga et al. [36] obtained PSD of 4.8 and 18.8 $m^2/s^{-4}/Hz$ for mediolateral, and vertical directions, respectively, on an aluminum MWC frame and in the critical 10–20 Hz frequency band. This result is in agreement with those of Maeda et al. [30], who reported that MWC users felt more discomfort for vibration in the vertical direction (79% of MWC users versus 8% and 13% for anteroposterior and mediolateral directions, respectively). Regarding anteroposterior, only Digiovine et al. [40] observed a lower T_{VDV} between the seat and the MWC users head in the anteroposterior direction than in the vertical direction (i.e., 0.9–2.1 and 2.4–7.3, respectively). Other articles [36,41,42] reported similar T_{VDV}, mean of acceleration, or PSD for the vertical and anteroposterior directions (see Table 2).

Table 2. Summary table of the reviewed studies regarding vibration direction: Vertical (V), anteroposterior (AP) and mediolateral (ML) direction.

Article	Method	Participant	Fs [Hz]	Parameters	Value			
					V	AP	ML	Norm
Maeda et al., 2003	Daily-life conditions	33 MWC users	—	Discomfort percentile (%)	79	13	8	—
Waga et al., 2020	Treadmill −5 km/h	Empty	100	PSD 0–10 Hz (Seat) PSD 10–20 Hz (Seat)	7.6–10.7 18.8–25.4	7.7–9.7 4.1–7.8	4.8–5.7 3.4–4.8	— —
Digiovine et al., 2003	Simulated road course	32 MWC users	200	T_{VDV} (Seat/Head)	2.4–7.3	0.9–2.1	—	2.4–7.4
Chenier et al., 2014	Simulated road course	10 AB	3200	t-Acc [m/s^2] (Seat)	Highest	Comparable to V	80% lower than V and AP	—
Digiovine et al., 2003	Simulated road course	10 AB	200	T_{VDV} (Seat/Head)	0.4–2.0	0.9–1.5	—	0.4–1.8

Finally, while all articles agreed on the low amount of vibration in the mediolateral direction compared to the vertical direction, the importance of the anteroposterior direction regarding the amount of vibration is still under-discussed.

3.2.2. Amount of Vibration

Fourteen articles studied the amount of vibration at which MWC users are exposed. The number of participants ranged from1 to 37, and the studied population were AB

(6 articles), MWC users (5 articles), or both AB and MWC users (1 article). One article was done with two dummies. Data were acquired during real daily-life propulsion (1 article), on different floor types (4 articles), over a simulated road course (3 articles), on curbs (3 articles), or on a drum shock simulator (2 articles). Accelerometers were placed on the seat (13 articles), on the backrest (2 articles), on the footrest (5 articles), on the MWC frame (5 articles), and/or on the participant's head (3 articles). Acceleration was observed along the three directions (3 articles), along the anteroposterior and vertical directions (6 articles), or the vertical direction only (5 articles); and with sampling frequencies above 200 Hz, except for one article (60 Hz). Parameters studied were a-RMS (2 articles), w-RMS (6 articles), VDV (3 articles), $P_{t\text{-}Acc}$ (7 articles), $P_{w\text{-}Acc}$ (2 articles), $P_{f\text{-}Acc}$ (2 articles), PSD (2 articles).

On the eight articles that addressed the amount of vibration transmitted to the MWC, six estimated the VDV and/or w-RMS, as recommended by the ISO 2631 standard for seated people [21]. Two articles measured a-RMS without applying frequency weight to the acceleration. For the seat, a-RMS or w-RMS were computed to investigate vibration and VDV for shock-induced vibration.

Despite differences in the time of exposure and evaluation method, articles agreed that MWC users are exposed to vibration levels exceeding the standards recommendations [31,41,43–46]. MWC users tend to be exposed to vibration for about 13 h per day [45]. The amount of vibration (i.e., w-RMS and VDV) at which MWC users are exposed was usually compared to the health caution zone limit for 8 h of exposure. As the time of exposure is, in reality, greater than eight hours, the health caution limit is exceeded. Besides, depending on ground surface properties (e.g., roughness), the limits of vibration exposure recommended by the ISO 2631 [21] and JIS B 7760-2 [47] standards are exceeded with a time of exposure between 1.6 and 13.4 h [46,48].

The amount of vibration at the footrest was only considered in three articles. Nevertheless, when MWC is considerate with a participant, articles reported a higher amount of vibration (i.e., a-RMS, and $P_{t\text{-}Acc}$) on the footrest than on the seat (i.e., 0.3–0.8 and 0.8–2.3 m/s^2 for the a-RMS on the seat and footrest, respectively [49]). Besides, the amount of vibration (VDV and w-RMS) at the backrest was found lower than at the seat (0.55 and 0.83 m/s^2, respectively [45]).

Besides, during over-ground propulsion, Garcia-Mendez et al. [45] showed that MWC users are exposed to inherent shocks with high amplitude. These shocks were also represented in experimental conditions. Many articles were done on a simulated road course with a drop, bump, or in a shock simulator. Shock generates high amplitude acceleration, explaining why $P_{t\text{-}Acc}$, $P_{w\text{-}Acc}$, and $P_{f\text{-}Acc}$ were observed in many articles studying shock during MWC propulsion (9 articles). However, a comparison of acceleration peaks between the articles is difficult. The method used to generate the shocks differed between the articles, which induced differences in acceleration. Hence, P_{Acc} varied noticeably between articles (see Table 3). For instance, on the seat, $P_{w\text{-}Acc}$ ranged from 8 to 33 m/s^2 for curb descent [50] and from 3 to 8 m/s^2 for propulsion on a simulated road course [51]. Drum shock simulator (inducing acceleration of 1 to 4 m/s^2) generates lower $P_{t\text{-}Acc}$ at the head than curb descent (13 to 17 m/s^2) [52,53]. Therefore, drum shock simulators apply on MWC lesser loads than curb descent in real daily-life conditions. Yet, the drum shock simulator is one of the methods currently used to test MWC in ISO standard [32].

Table 3. Summary table of reviewed studies regarding the investigation of the amount of vibration.

Articles	Method	Participant	Fs [Hz]	Measurements Point	Value						
					a–RMS [m/s^2]	w–RMS [m/s^2]	VDV [$m/s^{1.75}$]	P_{t-Acc} [m/s^2]	P_{w-Acc} [m/s^2]	P_{f-Acc} [m/s^2]	F–Acc [Hz]
Chenier et al., 2014	Simulated road course	10 AB	3200	Seat (V) Seat (AP, V)	— —	0.2–0.9 0.6–1.1	0.6–1.6 1.1–1.7	— —	— —	— —	— —
Hashizume et al., 2008	Slop (7) & Curb (6)	1 AB	—	Seat (Norm)	1–3	—	—	10–15	—	—	—
Duvall et al., 2013	Floor section (15)	32 MWC users	2000	Seat (V) Backrest (V) Footrest (V)	— — —	0.5–5.4 0.4–2.8 0.6–4.7	— — —	— — —	— — —	— — —	— — —
Garcia Mendez et al., 2013	Daily–life conditions	37 MWC users	60	Seat (AP, V) Backrest (AP)	—	0.83 0.55	17.3 12.1	— —	— —	— —	— —
Wolf et al., 2005	Floor section (6)	10 AB	1000	Seat (V)	—	0.3–0.8	—	—	—	—	—
Cooper et al., 2004	Floor section (6)	10 AB	1000	Seat (Norm) Footrest (Norm)	— —	— —	— —	— —	— —	5.3–18 14–41	2–10 4–12
Wolf et al., 2007	Floor section (9)	10 AB	200	Seat (V) Footrest (V)	— —	0.3–0.8 0.8–2.3	— —	— —	— —	— —	— —
Kwarciak et al., 2008	Curb (3)	1 SCI	200	Seat (V)	—	—	—	19–68	8–33	—	—
Hiscke et al., 2018	Simulated road course (4)	10 AB	2000	Seat (AP, V)		1.2–1.4	14–35	10–27	3–8	—	—
Requejo et al., 2008	Drum shock simulator	10 SCI	2000	Head (V) Head (AP)	— —	— —	— —	0.1–0.4 g 0.1–0.7 g	— —	— —	— —
Requejo et al., 2009	Curb (1)	8 SCI	2000	Head (V) Head (AP)	— —	— —	— —	1.3–1.7 g 1.1–1.9 g	— —	— —	— —
Vorrink et al., 2008	Simulated road course (9)	22 AB 13 SCI	1000	Footrest (AP, V) Frame (AP, V)	0.4 0.3	— —	— —	2.7–3.4 g 1.9–2.2 g	— —	— —	— —
Kerdanyan et al., 2005	Drum Shock simulator & Curb	11	—	Head (V)	—	—	—	0.8–2.0 g	—	—	—
Cooper et al., 2003	Drum shock simulator	2 dummies (100 & 72 kg)	1000	Seat (Norm) Footrest (Norm)	— —	— —	— —	— —	— —	6–18 6–19	7–10 4–15

Furthermore, lower $P_{w\text{-}Acc}$ value (i.e., 3–8 m/s^2 [51] and 8–33 m/s^2 [50]) than $P_{t\text{-}Acc}$ value (i.e., 10–27 m/s^2 [51] and 19–68 m/s^2 [50]) were observed, which indicates that acceleration peaks were above the frequency range that is deleterious for the human body.

3.2.3. Frequency Content of Vibration

Twenty articles studied vibration frequency. One article investigated only the MWC. For the other articles, the number of participants ranged from 2 to 32, and the studied population was AB (4 articles), MWC users (4 articles), or both AB and MWC users (1 article). Two articles were done with dummies. Data were acquired on different floor types (2 articles), over a simulated road course (5 articles), over a treadmill (1 article), on a vibrating platform (3 articles), or on a drum shock simulator (2 articles). Accelerometers were placed on the seat (4 articles), on the footrest (3 articles), on the MWC frame (6 articles), and/or on the participant's head (helmet or bite bar) (9 articles). Acceleration was observed along the three directions (6 articles), along the anteroposterior and vertical directions (2 articles), or along the vertical direction only (4 articles); and with sampling frequencies above 100 Hz. Frequencies of vibration to which MWC users are exposed were identified with an experimental modal analysis of the MWC (i.e., MWC eigenfrequencies) (3 articles), as the peaks of f-Acc (4 articles), or of $T_{f\text{-}Acc}$ (5 articles). $T_{f\text{-}Acc}$ were observed between the floor and the seat [30], between the MWC frame and the participant's head [31], through the cushion [54], between the seat and the participant's head [40,42], or the backrest and the participant's head [40,42].

The analysis of these articles shows that MWC users are exposed to vibration at frequencies deleterious for the seated human body (i.e., 4–12 Hz [21]). All articles identified at least one peak of acceleration (MWC eigenfrequencies, F_{Acc} on MWC, or $T_{t\text{-}Acc}$ between MWC and the user) in this frequency range: 4 Hz (4 articles), and 7 and 8 Hz (5 articles) (see Table 4). Moreover, these frequencies felt uncomfortable to MWC users. During a study on a vibrating platform (speed: 0.4 to 1 m/s; frequencies: 1 to 15 Hz), participants reported more discomfort for frequencies between 4 and 7 Hz [38].

As mentioned by Digiovine et al. [55], frequencies between 2 and 8 Hz could be associated with individuals' natural frequencies and frequencies at 15–16 Hz to the MWC. This is supported by Skendraoui et al. [39], who identified MWC eigenfrequencies at 16 Hz, 22–23 Hz, and 30 Hz through experimental modal analysis. However, for sport MWC's solely in dynamic conditions, frequencies lower than 15 Hz (i.e., 11–12 Hz) were observed for $P_{f\text{-}Acc}$ [36].

Table 4. Summary table of reviewed studies regarding vibration frequency during MWC propulsion.

Article	Method	Participant	Fs [Hz]	Value Facc [Hz] Frame (V)	Facc [Hz] Footrest (Norm)	Facc [Hz] Seat (Norm)	Facc [Hz] Seat (V)	Pabs [Hz] Seat (V)	T_{f-acc} [Hz] Seat/seat (V)	T_{f-acc} [Hz] Floor/seat (V)	Transfer function [Hz] Seat/head	Transfer function [Hz] Back/head	Transfer function [Hz] Frame/head (V)	F0 [Hz]
Maeda et al., 2003	Vibrating platform	10 AB	500	—	—	—	—	—	—	5–7 8 13–15	—	—	—	—
Vansickle et al., 2001	Simulated road course (8)	16 MWC users	960	—	—	—	—	—	—	—	—	—	8	—
Waga et al., 2020	Treadmill –5 km/h –10 km/h	Empty	100	12–13	—	—	—	—	—	—	—	—	—	—
Kawai et al., 2000	Vibrating platform	1	—	—	—	—	—	—	—	—	—	—	—	2 5 7 8
Skendraoui et al., 2019	Vibrating platform	Empty	500	—	—	—	—	—	—	—	—	—	—	16 23 31
Digiovine et al., 2003	Simulated road course (8)	32 MWC users	200	—	—	—	—	—	—	—	AP: 12–23 V: 7–13 norm: 16–23	AP: 13–23 V: 7–12 norm: 15–22	—	—
Digiovine et al., 2003	Simulated road course (10)	10 AB	200	—	—	—	—	—	—	—	AP: 25–50 V: 5–40 norm: 20–60	AP: 25–45 V: 5–35 norm: 20–55	—	—
Cooper et al., 2004	Floor section (6)	10 AB	1000	—	4–12	2–10	—	—	—	—	—	—	—	—
Garcia Mendez et al., 2012	Simulated road course (9)	14 AB	200	—	—	—	—	—	3	—	—	—	—	—
Digiovine et al., 1999	Simulated road course (8)	12 SCI	200	—	—	—	3.5 5.9 9.3 22.5 29.9	0.5 4 10.7 13.5 19.8 24.4	—	—	—	—	—	—

Table 4. *Cont.*

Article	Method	Participant	Fs [Hz]	Value										
				Facc [Hz]				Pabs [Hz]	$T_{f\text{–}acc}$ [Hz]		Transfer function [Hz]			F0 [Hz]
				Frame (V)	Footrest (Norm)	Seat (Norm)	Seat (V)	Seat (V)	Seat/seat (V)	Floor/seat (V)	Seat/head	Back/head	Frame/head (V)	
Cooper et al., 2003	Drum shock simulator	2 dummies (100 & 72 kg)	1000	—	11 ± 15 9 ± 10 15 ± 17 4 ± 2 9 ± 14 10 ± 11	9 ± 5 8 ± 5 10 ± 7 7 ± 2 8 ± 5 8 ± 5	—	—	—	—	—	—	—	—
Brown et al., 2017	Drum shock simulator	10 SCI	2000	—	—	—	—	—	—	—	—	—	—	4 & 7 2 & 12

3.2.4. Vibration Transmissibility

Six articles studied vibration transmissibility. One article considers the MWC only. For the other articles, the number of participants ranged from 10 to 32, and the studied population were AB (5 articles), or MWC users (1 article). Data were acquired over a simulated road course (5 articles), or a vibrating platform (3 articles). Accelerometers were placed on the seat (6 articles), on the MWC frame (1 article), or on the head (3 articles). Acceleration was observed along the three directions (2 articles), along the anteroposterior and vertical direction (1 article), or along the vertical direction only (4 articles); and with sampling frequencies above 200 Hz. Depending on the articles, parameters were observed for frequency ranges from 0–20 to 0–100 Hz. Parameters studied were $T_{a\text{-}RMS}$ (1 article), T_{VDV} (3 articles), $T_{t\text{-}Acc}$ (2 article), $T_{f\text{-}Acc}$ (1 articles).

Regarding T_{VDV} [40–42], $T_{w\text{-}RMS}$ [41,56], or transfer function between the floor and the seat [30], all articles reported value above one (see Table 5), which reveals that the MWC/user system tends to amplify the amount of vibration. Regarding $T_{f\text{-}Acc}$ through the cushion, Garcia-Mendez et al. [54] obtained values between 1 and 1.2. On the other hand, Digiovine et al. [56] reported that $T_{t\text{-}Acc}$ between the seat and the head was lower than one. Hence, the user/cushion system can reduce the shock amplitude, but not the vibration transmissibility (i.e., 0.4–0.5 and 1.3–1.4, for $T_{t\text{-}Acc}$ and $T_{a\text{-}RMS}$, respectively) [56].

3.2.5. Pathologies

Three articles studied MWC pathologies probably induced by vibration exposure. The number of participants ranged from 10 to 37, and the studied population was MWC users (2articles), or AB and MWC users (1article). Data were acquired in real daily-life conditions (1article), over a vibrating platform (3articles), as well as a survey (3articles). Accelerometers were placed on the seat (2articles), on the backrest (1article), and/or on a vibrating platform (1article). Acceleration was observed along the anteroposterior and vertical direction (1article), or along the vertical direction only (1article). Parameters studied were w-RMS (1article), T_{VDV} (1article), and the $T_{f\text{-}Acc}$ (1article).

Table 5. Summary table of reviewed studies regarding investigation vibration transmissibility.

Article	Method	Participants	Fs [Hz]	Measurements Point	T_{VDV}				T_{t-Acc}		T_{f-Acc}	T_{a-rms}	H
					V	AP	V + AP	Norm	V	V + AP	V	V	V
Maeda et al., 2003	Vibrating platform	10 AB	200	Floor/Seat	—	—	—	—	—	—	—	—	1.3–2.6
Digiovine et al., 2003	Simulated road course (9)	32 MWC users	200	Seat/Head	2.4–7.3	0.9–2.1	—	2.4–7.4	—	—	—	—	—
Chenier et al., 2014	Simulated road course (3)	10 AB	3200	Frame/Seat	0.4–1.5	—	0.5–1.0	—	0.4–1.5	0.5–1.0	—	—	—
Digiovine et al., 2003	Simulated road course (10)	10 AB	200	Seat/Head	0.4–2.0	0.9–1.5	—	0.4–1.8	—	—	—	—	—
Garcia Mendez et al., 2012	Simulated road course (9)	14 AB	200	Seat/Seat	—	—	—	—	—	—	1.0–1.2	—	—
Digiovine et al., 2000	Simulated road course (9)	10 AB	200	Seat/Head	—	—	—	—	0.4–0.5	—	—	1.3–1.4	—

Surveys revealed that MWC users complained about vibration transmitted at the neck, lower back, and buttocks [8,30]. Besides, Garcia-Mendez et al. [45] observed a prevalence of lower back pain in the MWC users population. Vibration levels (w-RMS, and VDV) did not differ between groups with and without low back pain (0.8 ± 0.1 m/s^2 vs. 0.9 ± 0.2 m/s^2, respectively) [45]. The relationship between vibration exposure and some of the MWC user's pains has not been assessed yet. However, despite this uncertainty, the frequencies of the transfer function peaks (i.e., 5–7, 8 and 12–15 Hz) along with MWC users' complaints (i.e., neck, lower back, and buttocks) identified by Maeda et al. [30] were consistent with the results of Whitham and Griffin [57]. This last article indicated that vertical vibration in the range of 4 to 16 Hz produced discomfort in both the upper torso and head [57].

3.3. Parameters Influencing Vibration Transmissibility

Regarding the 29 papers related to the parameters influencing vibration transmissibility during MWC propulsion, three sub-categories were outlined: Environmental parameters (i.e., floor surface, obstacles) (9 articles); MWC elements (i.e., frame (3articles), wheel (1article), suspensions (9articles), and cushions and backrest (9articles)); and users' parameters (i.e., speed, muscular control) (10articles).

3.3.1. Environmental Parameters

Nine articles studied the effect of environmental parameters on vibration transmissibility. The number of participants ranged from 10 to 32, and the studied population were AB (4articles), MWC users (3articles), or both AB and MWC users (1article). One article was done with a dummy. Data were acquired for different floor types (7articles), or on curbs descent and ascent (2articles). Accelerometers were placed on the seat (8articles), on the backrest (2articles), on the footrest (5articles), and/or on the MWC frame (1article). Acceleration was observed along the three directions (4articles), or along the vertical direction only (4articles); and with sampling frequencies above 200Hz. Parameters studied were a-RMS (1article), w-RMS (3articles), $P_{t\text{-}Acc}$ (2articles), $P_{w\text{-}Acc}$ (1article), $P_{f\text{-}Acc}$ (3articles), or PSD (1article).

Poured concrete (i.e., the most common pedestrian pathway; see Surface 1, Table 6) is one of the surfaces that induced the highest amounts of vibration whatever the observed parameter (i.e., w-RMS, PSD, or $P_{t\text{-}Acc}$) [46,48,49]. Interior laboratory granite surface and poured concrete showed similar values in w-RMS (0.15 and 0.2 m/s^2, respectively) [58]. Therefore, indoor and outdoor mostly used floors are those that induce the highest amount of vibration. Concrete Holland paver with no bevel (i.e., surface 2 on Table 6) is the pedestrian pathway with the lowest amount of vibration estimated by w-RMS, PSD, and $P_{t\text{-}Acc}$ [46,48,49].

The user's acceptability of the floor tends to decrease as surface roughness increases. On a 0 to 5 scale (where 5 reflects very good acceptability), floors with a 16 mm/m and 108 mm/m roughness, obtained a score of 4.4 and 1.8, respectively [44]. Furthermore, w-RMS tends to increase with the roughness of the floor (i.e., around 0.5 and 4 for floors with a 16 mm/m and 108 mm/m roughness, respectively [44,59]). w-RMS was also shown to increase with the floor aging (e.g., an increase of about 0.1 m/s^2 per year during the first three years [49]). Based on these observations, Duvall et al. [44,60] created the Pedestrian Roughness Index (PRI) to qualify a floor in terms of vibration transmitted to the MWC users. Depending on the floor PRI value, a "healthy" propulsion distance and exposure time were recommended. Hence, no limitation of distance and exposure time was done for a floor with a PRI inferior to 50 mm/m (e.g., surface 2 on Table 6). Floor with a PRI higher than 100 mm/m (e.g., chip and seal), the exposure time need to be shorter than 10 min. Poured concrete have a PRI of 45.5 mm/m. For such PRI, the limit of exposure time was set at 2 h. Measuring the 3D acceleration at the seat, an article observed that the ISO 2631 standard vibration exposure limit was exceeded from 2.8 h of exposure [48]). However, considering only the vertical axis, the ISO vibration exposure limit is exceeded later were found (e.g., from 6.8 h for the poured concrete [49]).

Table 6. Summary table of reviewed studies regarding the investigation of the effect of the floor type.

Article	Participant	Fs [Hz]	Measurement		Surface										
			Point	Parameters	1	2	3	4	5	6	7	8	9	10	11
Wolf et al., 2007/2005	10 AB	200	Seat (V)	w–RMS [m/s^2]	0.5 ± 0.1	0.3 ± 0.1	0.4 ± 0.1	0.8 ± 0.2	0.5 ± 0.1	0.5 ± 0.1	0.6 ± 0.1	0.8 ± 0.1	0.5 ± 0.1		
			Footrest (V)	w–RMS [m/s^2]	1.4 ± 0.2	0.8 ± 0.2	1.1 ± 0.2	2.3 ± 0.4	1.3 ± 0.3	1.4 ± 0.3	1.8 ± 0.3	2.2 ± 0.3	1.4 ± 0.2		
Cooper et al., 2004	10 AB	1000	Seat (norm)	P_{f-Acc} (0–120 Hz) [m/s^2]	13 ± 3	5 ± 2	9 ± 4	18 ± 2	10 ± 4	8 ± 2	—	—	—	—	—
			Footrest (norm)	P_{f-Acc} (0–120 Hz) [m/s^2]	36 ± 7	14 ± 5	19 ± 7	41 ± 4	24 ± 5	24 ± 6	—	—	—	—	—
			Seat (norm)	PSD 2.5–3.15 Hz	186 ± 124	10 ± 11	17 ± 20	193 ± 173	55 ± 38	61 ± 47	—	—	—	—	—
				PSD 4–5 Hz	460 ± 148	41 ± 47	68 ± 67	465 ± 337	124 ± 70	118 ± 75	—	—	—	—	—
				PSD 6.3–8 Hz	235 ± 129	31 ± 32	84 ± 95	459 ± 311	103 ± 77	103 ± 74	—	—	—	—	—
				PSD 10–12.5 Hz	403 ± 259	45 ± 71	77 ± 94	316 ± 308	76 ± 80	103 ± 88	—	—	—	—	—
Dziechciowski et al., 2017	2 AB 1 MWC users	—	Seat (V)	P_{f-acc} (8–20 Hz) [m/s^2]	0.2	—	—	—	—	—	—	—	—	0.2	2
Mitani et al., 2006	1 dummy	500	Frame (norm)	P_{f-acc} [m/s^2]	Floor section (Tactile walking surface indicators)										
Duval et al., 2013/2016	32 MWC users	2000	Seat (V) Backrest (V) Footrest (V)	w–RMS [m/s^2]	Floor section (15)										
Hashizume et al., 2008	1 AB	500	Seat (norm)	RMS [m/s^2] P_{t-Acc} [m/s^2]	Curb & slop										
Kwarciak et al., 2008	1 SCI	200	Seat (V)	P_{t-acc} [m/s^2] P_{w-acc} [m/s^2]	Curbs descent	Folding Al (P_{t-acc})	Folding Al (P_{w-acc})	Rigid Al (P_{t-acc})	Rigid Al (P_{w-acc})	Rigid Ti (P_{t-acc})	Rigid Ti (P_{w-acc})				
					−5 cm	28–35	13–18	21–34	8–15	21–30	9–15				
					−10 cm	40–52	20–27	35–47	15–23	33–50	14–23				
					−15 cm	45–70	29–36	52–62	24–34	52–75	20–34				

Tactile walking surface indicators are sometimes added to the floor to help visually impaired people. Such a surface may affect the amount of vibration transmitted to MWC users. Dotted and bar blocks, which are recommended by JIS standard [47], reduced the amount of vibration by one-third and a half, respectively, compared to what was commonly used in Japan [37].

In daily life, MWC users are also exposed to change in height through slopes and/or curbs. For both ascent and descent, slopes allowed a smaller amount of vibration than curbs. Ascending the same change of height, a lower amount of vibration was observed for slope (e.g., 7 and 1 m/s^2 for $P_{t\text{-}Acc}$ and a-RMS, respectively, for a 2 cm height) than for curbs (e.g., 16 and 3 m/s^2 for $P_{t\text{-}Acc}$ and a-RMS, respectively, for a 2 cm height) [43]. Even though ascending the 1–2 cm curbs produced higher $P_{t\text{-}Acc}$ than descending them (e.g., 10 m/s^2 for 2 cm of curbs) [43], descending slopes still produced lower $P_{t\text{-}Acc}$ than curbs (e.g., 7 and 12 m/s^2, for slopes and curbs, respectively [43]).Using slopes instead of curbs is more interesting if the change in height is important. Indeed, $P_{t\text{-}Acc}$ and $P_{w\text{-}Acc}$ on the seat increase with the height of the curb (e.g., $P_{t\text{-}Acc}$ was 19. 41 and 68 m/s^2 for curbs of 5, 10, and 15 cm height, respectively [50]).

3.3.2. MWC Elements

Frame

Three articles reported the effect of the frame regarding vibration transmissibility. The number of participants ranged from1 to 10, and the studied population were AB (1 article), or MWC users (1 article). Data were observed over a simulated road course (1 article), a treadmill (1 article), or a drum shock simulator (1 article). Accelerometers were placed on the seat (3 articles), on the footrest (1 article), and/or the MWC frame (1 article). Acceleration was observed along the three directions (1 article), along the anteroposterior and vertical direction (1 article), or along the vertical direction only (1 article). The sampling rate was at least 100 Hz. Studied parameters were a-RMS (1 article), w-RMS (1 article), VDV (1 article), $P_{t\text{-}Acc}$ (1 article), $P_{w\text{-}Acc}$ (1 article), PSD (1 article), $T_{w\text{-}RMS}$ (1 article), or T_{VDV} (1 article). MWC considered in the articles were folding (1 article), rigid (1 article), or both folding and rigid MWC (1 article). For all articles, the material of the studied MWC frame was aluminum, except for Chénier et al. [41], who also studied carbon and titanium MWC, and for Waga et al. [36], who also studied a magnesium MWC.

Change of MWC type (i.e., rigid or folding) always involved a change of MWC design. Results showed that MWC type may not affect $P_{t\text{-}Acc}$ and $P_{w\text{-}Acc}$ at the seat. For a given MWC frame material, no significant difference was observed in $P_{t\text{-}Acc}$ and $P_{w\text{-}Acc}$ values at the seat (see Table 5) between the folding and the rigid MWC groups [50].

The influence of the folding frame design (i.e., one single cross-brace, one tri-cross-brace, two single cross-brace, or one dual cross-brace) was also investigated. No difference was observed in w-RMS or VDV values at the seat between frame designs [41]. On the other hand, $T_{w\text{-}RMS}$ between the MWC frame and the seat tends to be higher for two single cross-braces design than for other designs (e.g., 1.15, 1.39, 1.75, and 1.41 for two single cross-braces and other design, respectively, for propulsion on a smooth vinyl) [41] (see Table 7).

Table 7. Summary table of reviewed studies regarding the effect of the frame on the vibration content.

Article	Method	Participant	Fs [Hz]	MWC Type	Frame Design	Material	Value							
							Seat (V)				Frame (V)		Frame/Seat (V)	
							$P_{t\text{–}acc}$ [m/s^2]	$P_{w\text{–}acc}$ [m/s^2]	w–RMS [m/s^2]	VDV [m/s$^{1.75}$]	a–RMS [m/s^2]	PSD 10–20 Hz [(m/s^2)^2]	$T_{w\text{–}RMS}$ [%]	T_{VDV} [%]
Waga et al., 2020	Treadmill −5 km/h −10 km/h	Empty	100	Rigid	Sport	Al	—	—	—	—	0.02 0.10	19 75	—	—
						Mg	—	—	—	—	0.02 0.06	25 49	—	—
						Mg + weight	—	—	—	—	0.02 0.06	24 52	—	—
Chenier et al., 2014	Simulated road course - Vinyl - Textured rubber - Obstacles	10 AB	3200	Folding	One signle cross–brace	Carbonfiber	—	—	0.25 0.44 0.86	0.58 0.91 1.50	—	—	128 30 55	126 31 42
						Ti	—	—	0.25 0.44 0.78	0.56 0.92 1.43	—	—	172 36 60	164 37 47
						Al	—	—	0.22 0.40 0.79	0.54 0.84 1.41	—	—	122 36 54	115 36 43
					One tri–cross–brace	Al	—	—	0.25 0.48 0.79	0.58 0.98 1.52	—	—	144 33 61	139 33 48
					Two signle cross–brace	Al	—	—	0.24 0.46 0.87	0.61 1.00 1.57	—	—	171 45 62	175 47 50
					One dual cross brace	Al	—	—	0.23 0.50 0.86	0.53 1.01 1.56	—	—	149 33 62	141 34 47.5
Kwarciak et al., 2008	Curbs descent −5 cm −10 cm −15 cm	1 SCI	200	Folding	—	Al	28–35 40–52 45–70	13–18 20–27 29–36	—	—	—	—	—	—
				Rigid	—	Al	21–34 35–47 52–62	8–15 15–23 24–34	—	—	—	—	—	—
				Rigid	—	Ti	21–30 33–50 52–75	9–15 14–23 20–34	—	—	—	—	—	—

Regarding MWC frame material, no effect on $P_{t\text{-}Acc}$ and $P_{w\text{-}Acc}$, w-RMS, and VDV was observed. Differences were only observed on a magnesium MWC, which exhibited a lower a-RMS than aluminum sport MWC (i.e., 0.06 m/s^2 vs. 0.1 m/s^2 [50]) for high speed only (2.8 m/s).

Wheel

One article reported the effect of the wheel on vibration transmissibility. Participants were 22 AB and 13 MWC users. Data were observed over a simulated road course. Accelerometers were placed on the footrest and the MWC frame. Acceleration was observed along the anteroposterior and vertical directions. The sampling rate was 1000 Hz. Parameters studied were a-RMS and $P_{t\text{-}Acc}$.

Traditional steel-spoked wheels were compared to Spinergy wheels, including a triple-cavity rim, an alloy hub with one-piece construction, and carbon-fiber spokes originating from the hub. Results showed no difference between steel-spoked and Spinergy wheels on both a-RMS and $P_{t\text{-}Acc}$ acceleration [61].

Suspension

Nine articles reported the effect of the suspension on vibration transmissibility. The number of participants ranged from1 to 37, and the studied population were AB (1 article), or MWC users (6 articles). Two articles used dummies. Data were acquired during real daily-life conditions (1 article), on different floor types (1 article), on curbs (2 articles), over a simulated road course (1 article), on a vibrating platform (1 article), or on a drum shock simulator (3 articles). Accelerometers were placed on the seat (7 articles), on the backrest (1 article), on the footrest (1 article), on the MWC frame (5 articles), and/or on the participant's head (4 articles). Acceleration was observed along the three directions (2 articles), along the anteroposterior and vertical direction (5 articles), or along the vertical direction only (2 articles). The sampling rate varied from 60 to 2000 Hz. Studied parameters were w-RMS (2 articles), VDV (2 articles), $P_{t\text{-}Acc}$ (5 articles), $P_{w\text{-}Acc}$ (2 articles), $P_{f\text{-}Acc}$ (2 articles), or PSD (1 article).

The suspension could be mounted at the frame (i.e., rear-wheel suspensions) or at the caster fork (Figure 2). Regarding rear-wheel suspension, rigid and folding MWC frames were investigated. All articles compared MWC models with suspensions to MWC models without suspension, implying that no MWC was studied with and without suspensions. The suspension system could be separated into three main types: Polymer-based shock suspension (e.g., Barracuda, or A6-S), spring suspension (e.g., Boing!), or spring damper suspension (e.g., Quickie XTR). Four suspended MWC models (Boing!, Quickie XTR, Barracuda, and A6-S) were used in many articles (Figure 2). However, articles differed in terms of experimental conditions, considered MWC, and observed parameters.

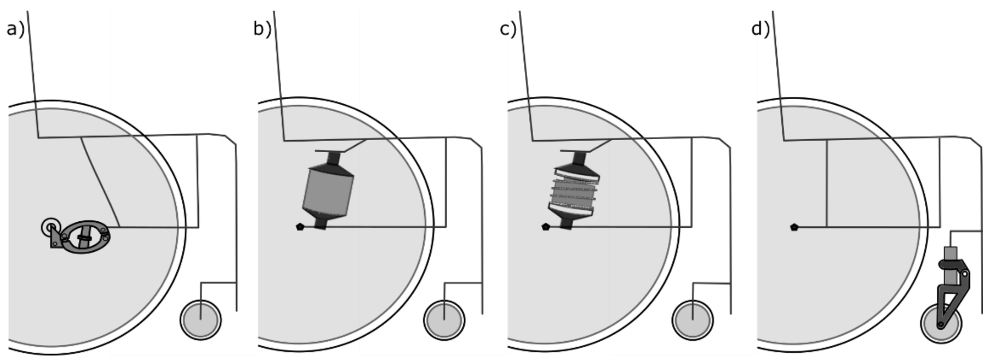

Figure 2. Representation of polymer-based shock (**a**,**b**), and spring damper (**c**) rear-wheel suspension, and a type of caster fork suspension (**d**).

Regarding the amount of vibration, the efficacy of rear-wheel suspension in decreasing vibration is questionable. Although some articles indicated no difference between suspended and conventional MWC [8,45], other articles revealed that suspension decreased the amount of deleterious vibration [50,51,62]. Moreover, a significant difference was observed only for some MWC (i.e., Quickie XTR suspended MWC) [50].Besides, under certain conditions, a suspended MWC induced a higher amount of vibration than a conventional MWC (see Table 8).

Moreover, suspensions decrease the amount of vibration induced by a shock. Differences were observed on $P_{t\text{-}Acc}$ and $P_{w\text{-}Acc}$ during the shock simulation experiment [50,51]. MWC, which reported the lowest amount of vibration, was suspended (i.e., Quickie XTR MWC, spring damper suspension) [50,52,53]. Yet, as suspensions are designed to absorb vertical shock, their capability to absorb the 3D components of vibration is limited. Kwarciak et al. [50] revealed that the amount of vibration reaching the MWC was higher when the solicitation was not aligned with the suspension direction. However, the comparison was done using MWC with different types of suspension or over different curbs' heights. A lower value of $P_{t\text{-}Acc}$ and $P_{w\text{-}Acc}$ at the seat may be caused by a lower curb's height or by better absorption of the MWC or the suspension. Polymer-based shock suspensions have been shown to absorb fewer vibrations than other suspension types [50].

Through an MWC/user model, Matsuoka et al. [63] investigated the suspension efficacy with respect to their damping and stiffness elements. A decrease in the stiffness coefficient was associated with a decrease in the frequency of $T_{f\text{-}Acc}$ from the floor to the participant's torso (e.g., about 4.5 Hz for a 107 N/m stiffness coefficient, and 2.5 Hz for a 10^2 N/m stiffness coefficient). The amplitude of the $T_{f\text{-}Acc}$, for its part, increases from 4.4 to 5, for stiffness coefficient between 107 N/m and 105 N/m and then decrease to 2 for 102 N/m. Frequency and amplitude reduction tended to overload for stiffness coefficient around 104 N/m. Regarding damping, a minimum of vibration transmissibility was obtained for a damping coefficient of 104 Ns/m [63]. Conventional MWC may be simulated as an infinite stiffness element associated with a damping element of 1 Ns/m. Therefore, suspensions seem to decrease vibration frequency. Although it most likely affects the vibration transmissibility, the effect of the damping coefficient on the frequency content was not addressed. Over a drum shock simulator, Cooper et al. [64] observed that rear-wheel suspensions tend to increase the vibration frequencies. MWC with suspension had a lower PSD than conventional MWC for the bandwidth of 7–9 Hz. However, the PSD for the bandwidth of 12–15 Hz was higher for the suspended MWC than conventional MWC (see Table 8).

Table 8. Summary table of reviewed studies regarding the effect of suspensions on the vibration content.

Article	Method	Participant	Fs [Hz]	Measurements		Conditions	Rear Wheel Suspension					Rigid	Folding	Casterfork	
				Point	Parameters		XTR	A6S	Barracuda	Boing!	Others			With	Without
Mitani et al., 2006	Floor section	1 dummy	500	Frame (norm)	$P_{f\text{-}acc}$ [m/s^2]	—	—	—	—	—	—	—	—	90 *	20 *
Garcia–Mendez et al., 2013	Daily–life conditions	37 MWC users	60	Seat (AP, V)	w–RMS [m/s^2]	—	—	—	—	—	0.8 ± 0.2	0.8 ± 0.2	0.9 ± 0.1	—	—
					VDV [m/s$^{1.75}$]	—	—	—	—	—	18 ± 4	17 ± 3	17 ± 3	—	—
				Backrest (AP)	w–RMS [m/s^2]	—	—	—	—	—	0.6 ± 0.2	0.5 ± 0.1	0.6 ± 0.1	—	—
					VDV [m/s$^{1.75}$]	—	—	—	—	—	12 ± 3	12 ± 3	12 ± 2	—	—
Kwarciak et al., 2008	Curbs descent	1 SCI	200	Seat (V)	$P_{t\text{-}acc}$ [m/s^2]	Curb height −5 cm *	17 ± 1	19 ± 2	27 ± 2	19 ± 1	—	21 – 34	28 – 35	—	—
						−10 cm *	28 ± 4	41 ± 8	33 ± 8	32 ± 5		33 – 50	40 – 52		
						−15 cm	33 ± 4	68 ± 17	61 ± 16	51 ± 12		52 – 74	45 – 70		
					$P_{w\text{-}acc}$ [m/s^2]	−5 cm *	5.0 ± 1	8 ± 2	12 ± 1	9 ± 1	—	8 – 15	13 – 18	—	—
						−10 cm *	11 ± 2	17 ± 2	17 ± 4	16 ± 2		14 – 23	20 – 27		
						−15 cm	15 ± 1	24 ± 4	29 ± 8	21 ± 3		20 – 34	25 – 35		
Hischke et al., 2018	Drum shock simulator	10 AB	1000	Seat (AP, V)	$P_{t\text{-}Acc}$ * [m/s^2]	−Door threshold −2 cm curb ascent −2 cm curb descent	—	—	—	—	23 ± 10 * 47 ± 9 * 37 ± 14 *	27 ± 10 * 48 ± 15 * 43 ± 18 *	—	—	—
					$P_{w\text{-}Acc}$ * [m/s^2]	−Door threshold −2 cm curb ascent −2 cm curb descent	—	—	—	—	6 ± 1 * 8 ± 2 * 6 ± 1 *	5.4 ± 1.3 * 8.4 ± 1.8 * 5.3 ± 1.6 *	—	—	—
					w–RMS [m/s^2]	- Truncated domes	—	—	—	—	1 ± 0	1 ± 0	—	—	—

Table 8. *Cont.*

Article	Method	Participant	Fs [Hz]	Measurements		Conditions	Rear Wheel Suspension					Rigid	Folding	Casterfork	
				Point	Parameters		XTR	A6S	Barracuda	Boing!	Others			With	Without
					VDV [m/s$^{1.75}$]	- Door threshold −2 cm curb ascent −2 cm curb descent −Truncated domes	—	—	—	—	18 ± 3 21 ± 4 24 ± 4 14 ± 1	20 ± 4 22 ± 4 30 ± 5 15 ± 3	—	—	—
Requejo et al., 2008	Drum shock simulator	10 SCI	2000	Head (V)	$P_{t\text{–}Acc}$ [g]	Speed −1.3 m/s^2	0.1	—	—	0.1	—	0.3	—	—	—
				Head (AP)	$P_{t\text{–}Acc}$ [g]	Speed −1.3 m/s^2	0.3–0.5	—	—	0.2–0.3	—	0.4–0.7	—	—	—
Requejo et al., 2009	Curbs descent	8 paraplegia	2000	Head (V)	$P_{t\text{–}acc}$ [m/s^2]	Curb height −5 cm	1.3 ± 0.3	—	—	1.6 ± 0.4	—	1.7 ± 0.4	—	—	—
Cooper et al., 2003	Drum shock simulator	2 dummies [100 & 72 kg]	1000	Seat (V)	$P_{f\text{–}acc}$ [m/s^2] Freq. [Hz] PSD [7–9 Hz] PSD [12–15 Hz]	— — — —	13 10	± ± 0.3 2	1 7 *	— — — —	— — — —	11 ± 1 7 ± 2 * 0.6 1.3		6 ± 4 * 8 ± 5 0.2 ± 0.1 1.0 ± 0.4	18 ± 2 * 8 ± 5 0.7 ± 0.6 2.4 ± 1
				Footrest (V)	$P_{f\text{–}acc}$ [m/s^2] Freq. [Hz] PSD (7–9 Hz) PSD (12–15 Hz)	— — — —	13 15	± ± 0.6 3	6 17 *	— — — —	— — — —	12 ± 9 4 ± 2 * 0.6 1.2		6 ± 4 * 10 ± 11 0.4 ± 0.2 1.5 ± 2.1	19 ± 11 * 9 ± 14 0.8 ± 0.4 2.8 ± 1.7
Kerdanyan et al., 2005	Drum shock simulator	11 MWC users	2000	Head (V)	$P_{t\text{–}Acc}$ [g]	—	—	—	—	0.1	—	1	—	—-	—-

* Significant difference observed between MWC group (i.e., folding, rigid, suspended, MWC with caster fork suspension).

Contrary to rear-wheel suspension, the presence of caster fork suspension decreases the amount of vibration by a factor of two to three [37,64]. Over a drum shock simulator, Cooper et al. [64] measured $P_{f\text{-}Acc}$ values of 18.2 and 6.3 m/s^2 at the seat of MWC with standard manufacturer casters and MWC with polymer-based suspension caster forks, respectively. No change in F_{Acc} was observed (8–10 Hz) between standard original equipment manufacturer and polymer-based suspension caster forks [64] (see Table 8).

Cushion and Backrest

The effect of the cushion and the backrest regarding vibration transmissibility was investigated in 10 and 2 articles, respectively. Three articles were done without participants. For other articles, the number of participants ranged from2 to 32, and the studied population was AB (3 articles), MWC users (2 articles), or both AB and MWC users (1 article). Data were acquired over a simulated road course (10 articles), on a vibrating platform (1 article), or using an indenter drop (i.e., ISO 16840 standard) (3 articles). Accelerometers were placed on the seat (9 articles), and/or on the participant's head (3 articles). Acceleration was observed along the three directions (3 articles), or along the vertical direction only (6 articles). The sampling rate varied from 200 to 1000 Hz. Parameters studied were varied: a-RMS (1 article), $P_{t\text{-}Acc}$ (1 article), $T_{f\text{-}Acc}$ (1 article), $T_{t\text{-}Acc}$ (1 article), $T_{a\text{-}RMS}$ (1 article), T_{VDV} (2 articles), transfer function (1 article). Rigid and folding MWC frames were considered. The cushion can be classified into four different types as foam, air + foam, gel + foam, or air. Four types of backrest were also considered: nylon, foam, air +foam, and foam with a rigid plate.

Seat cushion amplified vibration in the range of frequency deleterious for the seated human body (i.e., 4–12 Hz) [40,42,54,56]. The only study observing vibration through the cushion over a simulated road course reported $T_{f\text{-}Acc}$ values from 1 to 1.2 at frequencies from 3.1 to 3.5 Hz [54]. However, regarding isolated cushions during ISO 16840-3 testing [32], higher F_{Acc} were observed (i.e., 4 and 8 Hz [65]) above the isolated cushion than through the cushion loaded by a participant. The preload induced by the participant mass affects the stiffness and damping properties of the cushion [54] (see Table 9), and as a consequence, vibration transmissibility through the cushion.

The performance of the cushion regarding vibration transmissibility depends on observed parameters (T_{VDV} or transfer function). Jay sunrise (gel + foam) cushion was the cushion with the lowest T_{VDV}, but also the highest transfer function magnitude peak [40,42]). Contrary to the transfer function, T_{VDV} is based on frequency-weighted acceleration, and consequently, T_{VDV} did not consider only the amplitude of vibration nor the frequency content. If vibration transmitted is in the frequency range of vibration deleterious for the human body, the cushion that transmits a lesser amount of vibration may not always be the healthiest. Therefore, to study vibration transmitted to the human body observing the amplitude of vibration is not enough, the frequency content of the vibrations must also be taken into account [40,42].

Table 9. Summary table of reviewed studies regarding the effects of cushion on vibration content.

Article	Method	Participant	Fs [Hz]	Measurements		Condition		Cushion												
				Point	Parameters			Foam			Gel	Gel + Foam			Air			Air+foam		
Digiovine et al., 2003	Simulated road course (8)	32 MWC users	200	Head/seat	T_{VDV} (V)	—		8	±	0	—	8	±	0	8	±	0	8	±	0
					T_{VDV} (norm)	—		8	±	0	—	8	±	0	8	±	0	8	±	0
					F(H) (V) [Hz]	—		13	±	2	—	12	±	2	13	±	2	14	±	2
					F(H) (norm) [Hz]	—		21	±	3	—	22	±	3	23	±	3	18	±	3
Garcia mendez et al., 2012	ISO 16840 standard	None	200	Seat	C [kNs/m]	Preload	300 N		57		60		27		32	–	51		40	
							800 N		183		175		40		69	–	95		76	
					K [N/m]		300 N		487		573		365		544	–	544		301	
							800 N		1689		1507		571		1015	–	1015		397	
	Simulated road course (8)	14 AB	200	Seat under the cushion/ Seat bove the cushion	Tf–Acc (V)	—			1.2		1.1		1.0		1.2	–	1		1.2	
					F–tfAcc (V) [Hz]	—			3.2		3.4		3.5		3.1	–	3		3.3	
Skendraoui et al., 2019	Vibrating platform	2 AB	500	Tosro	a–RMS [m/s^2]	Subject mass	65 kg		0.2		—		—			0.3			—	
							94 kg		0.2		—		—			0.2			—	
				Frame	a–RMS [m/s^2]		65 kg		0.3		—		—			0.3			—	
							94 kg		0.2		—		—			0.3			—	
Digiovine et al., 2000	Simulated road course (9)	10 AB	500	Head/seat	Tpt–Acc (V)	—		0.5	±	0.1	—	0.5	±	0.1	0.5	±	0.1	0.4	±	0.1
					Ta–RMS (V)	—		1.4	±	0.2	—	1.4	±	0.2	1.4	±	0.2	1.3	±	0.2
Ferguson et al., 2015	ISO 16840 standard	None	1000	Seat	Rebound ratio	—								0.4–0.6						
					Impact ratio	—								0.3–0.4						
Chung et al., 2009	ISO 16840 standard	None	200	Seat	Rebound ratio	—			0.2–0.5		—		—			—			—	
					Impact ratio	—			0.1–0.4		—		—			—			—	
Wolf et al., 2004	Simulated road course (9)	32 MWC users	200	Seat	Pabs (V) [Nm/s]	—		206	±	97		212	±	101	211	±	106	198	±	92
Sprigle et al., 2010	ISO 16840 standard	None	200	Seat	Rebound ratio	—			0.4		0.8		0.5			0.8			—	
					Impact ratio	—			0.1		0.2		0.2			0.3			—	

Cushions affect the postural support and vibration transmissibility in anteroposterior and vertical directions [40,66]. Through the ISO 16840 standard testing (approach summarized Appendix C), differences between the cushions were observed on the damping capacity, defined as the ratio between the acceleration's peak at the first and second impact. The damping capacity was 0.14, 0.34–0.38, and 0.22–0.26, for foam cushion, gel with or without foam cushion, and air cushion, respectively. Therefore, foam tends to offer better stability (i.e., lower ratio), whereas air cushion offers the worst stability (i.e., higher ratio). Cushion types allowing the lowest transmissibility differed for AB participants and MWC users. Meanwhile, cushions with foam and air lowered vibration transmissibility compared to other cushion types for AB (see Table 9) [42,54,56,67], no difference was observed for MWC users.

The backrest was less studied than the cushion (2 vs. 10 articles, respectively). Regarding backrest, differences were observed in the time domain, but not in the frequency domain, for both AB and MWC users. Regarding AB participants and MWC users, the backrest with air and foam (Fastback backrest model) and the nylon backrest (Nylon sling back backrest model) conveyed to the lowest T_{VDV} between the seat and the participant's head, respectively (see Table 10) [40,42].

Table 10. Summary table of reviewed studies regarding the effects of backrest on vibration content.

Article	Method	Participant	Fs [Hz]	Measurements		Backrest			
				Point	Parameters	SB	PB	JAB	VFB
Digiovine et al., 2003	Simulated road course (8)	32 MWC users	200	Head/seat	T_{VDV} (V)	8 ± 0	8 ± 0	8 ± 0	8 ± 0
					T_{VDV} (norm)	8 ± 0	8 ± 0	8 ± 0	8 ± 0
					F(H) (V) [Hz]	12 ± 2	12 ± 2	15 ± 3	12 ± 2
					F(H) (norm) [Hz]	19 ± 3	21 ± 3	21 ± 3	22 ± 3

Interestingly, DiGiovine et al. [34] outlined that MWC users seem not to optimize their MWC's cushion and backrest with respect to vibration transmissibility. Over a simulated road course, DiGiovine et al. [40] tend to measure higher T_{VDV} from the seat to the participant's head using the participant's cushion and backrest than using the optimized cushion and backrest (7.8 ± 0.3 and 7.2 ± 0.3).

3.3.3. Participant Parameters

Ten articles reported the effect of the participant regarding vibration transmissibility. Through their body characteristics (e.g., weight, muscular control), but also their propulsion technique or their speed, participants could affect vibration transmissibility. One article used two dummies, and two articles used an {MWC + user} numerical model. For others articles, the number of participants ranged from 1 to 35, and the studied population were AB (1 article), MWC users (3 articles), or both AB and MWC users (2 articles). Data were acquired over a simulated road course (3 articles), during a curb descent (1 article), on a vibrating platform (2 articles), or on a drum shock simulator (2 articles). Accelerometers were placed on the seat (6 articles), footrest (3 articles), MWC frame (3 articles), and/or participant's head (2 articles). Acceleration was measured along the three directions (4 articles), along the anteroposterior and vertical directions (4 articles), or along the vertical direction only (1 article). The sampling rate varied from 200 to 2000 Hz. Studied parameters were: a-RMS (1 article), $P_{t\text{-}Acc}$ (3 articles), $P_{f\text{-}Acc}$ (1 article), or PSD (1 article), T_{VDV} (2 articles), $T_{f\text{-}Acc}$ (1 article), transfer function (2 articles), and eigenfrequencies (1 article).

Regarding the effect of the participant mass on the frequency content, over a vibrating platform, Skendraoui et al. [39] identified changes in the PSD amplitude at 6 and 16 Hz. At 6 Hz, the PSD amplitude of the heavier participant (94 kg) was five-time lower than for the lighter participant (65 kg). The opposite result was observed at 16 Hz. However, no difference was outlined on the RMS of f-Acc. Therefore, participant mass seemed to mostly influence the repartition of the frequency content, but not the amount of vibration. Contrary to Skendraoui et al. [39], over a drum shock simulator, Cooper et al. [64] reported no difference in the PSD at the seat, neither for the amplitude nor the frequency, using dummies of different weights instead of real participants.

Muscular control affects the amount of vibration reaching the participant [68,69]. Over a simulated road course, a lower T_{VDV} between the seat and the participant's head was observed in both vertical and anteroposterior directions for AB participant (0.4–1.8 and 0.9–1.4, respectively) than for MWC users (2.4–7.3 and 0.9–2.1, respectively) [40,42]. MWC users with a high level of SCI had a higher $P_{t\text{-}Acc}$ at the head in the anteroposterior direction (2.2 ± 0.6 m/s^2) than low SCI participants (1.2 ± 0.8 m/s^2) [52]. Yet, in the vertical direction, no difference was observed (1.6 ± 0.6 m/s^2 and 1.7 ± 0.4 m/s^2 for high and low SCI, respectively). Although the displacement speed was lower for high SCI than for low SCI and that the vibration level is known to be increased with the speed [52,61], results suggest that a higher capability in muscular control modulate the vibration transmissibility through the human body. Muscular control also affects the frequency content of vibration. Through a modelization, Brown et al. [70] obtained different eigenfrequencies for SCI-C6 (3.6 and 7.1 Hz) and SCI-T7 (2.3 and 12 Hz) MWC users representation.

Posture and propulsion technique also seems to affect vibration. Based on numerical simulations, Matsuoka et al. [63] found a higher $T_{f\text{-}Acc}$ between the seat and the upper torso in a forward posture than in a normal erect posture for different segment's lengths (6 and 4, respectively). Besides, regarding propulsion technique, during curbs descent, a lower $P_{t\text{-}Acc}$ on the seat was observed when participants used the pull-up technique (10–15 m/s^2) compared to a simple drop (20–25 m/s^2) [53].

3.4. Modeling of Vibration Transmissibility

Six articles focused on the modeling of vibration transmissibility for MWC/user system. Models were developed thanks to experimental data with numbers of participants ranging from1 to 14, and the studied population was AB (3 articles), MWC users (1 article), or both AB and MWC users (2 articles). Data were observed over a simulated road course (1 article), a curb descent (1 article), on a vibrating platform (3 articles), or on a drum shock simulator (1 article). All the models were 2D models in the sagittal plane. The types of models used were analytical models (i.e., mass-spring-damper) (4 articles), a finite element model (FEM) (1 article), or an equation based on statistic regression (1 article).

Regarding the analytical models (Figure 3), one focused on the cushion solely [54], whereas others focused on the MWC user, modeled either as three [70,71] or five segments [38,63]. Only one model, used in two studies [38,63], considered the whole MWC, which was modeled as a single rigid body. The anthropometric data of the participant were estimated through a classical anthropometric table initially defined for athletes [72,73].

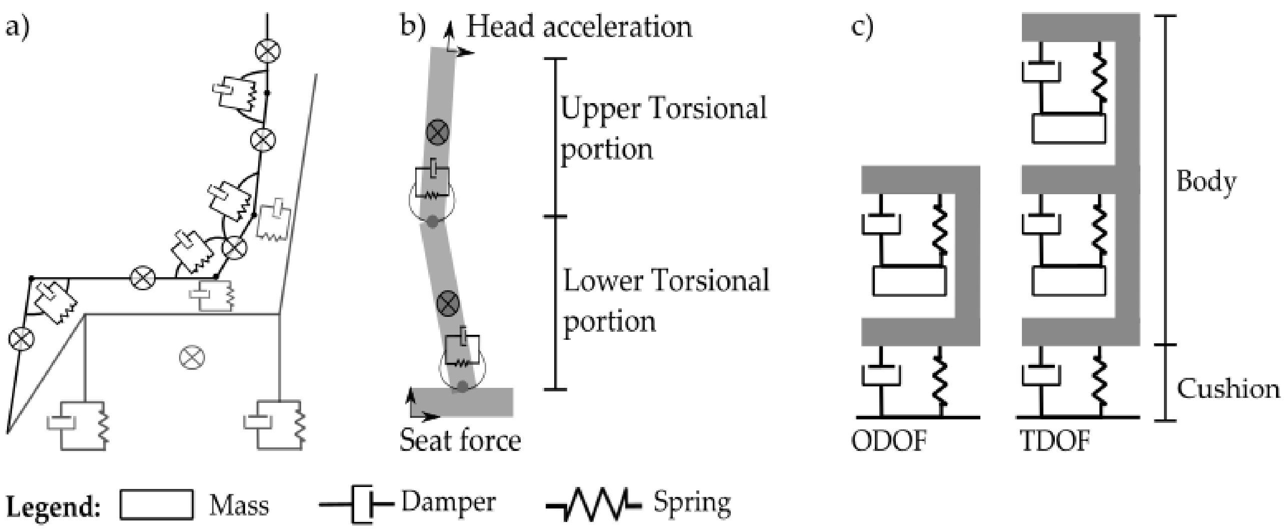

Figure 3. Representation of the mechanical models developed by Kawai et al. and Mastuoka et al. (**a**) Brown et al. (**b**), and Garcia-Mendez et al. (**c**).

A mechanical model of the MWC user was developed by Kawai and Matsuoka [38]. The model's parameters were obtained through a curve fitting procedure between estimated and experimental acceleration at each segment. The obtained results were validated by two different methods: First, the simulated model movement was compared to the video of the participant during the experiment [38]; and second, by comparing simulated and experimental transmissibility signals between the seat and the upper torso. Matsuoka et al. [63] then used this model to study the effect of the posture on the vibration transmissibility between the seat and the upper torso. Consequently, the developed model can represent the diversity of MWC users in terms of posture and height, and find the best posture in terms of vibration transmissibility. This model could also be used to optimize the MWC, for instance, to determine the suspension coefficient to minimize the vibration transmissibility from the seat to the upper torso.

Brown et al. [70,71] proposed an analytical model to predict head acceleration in the sagittal plan knowing the forces at the seat. This model considers the level of impairment of the MWC users. The model validation was done with experimental data obtained over a drum shock simulator for a speed typical of daily life, i.e., about 1.0 m/s, for MWC users with various SCI levels (i.e., C6 to L4–L5). Parameters of the transfer function and of the model were identified from the experimental data using a Maximum Likelihood estimation. Based on the seat force, simulated and experimental vertical and anteroposterior head accelerations were compared to validate the model. When comparing simulations for different degrees of freedom (2 to 6), the two degrees-of-freedom models were highlighted to represent the best dynamics of MWC users (Figure 3).

The Garcia-Mendez et al. [54] model was intended to investigate the vibration transmissibility through the cushion. In this model, the MWC was not considered, and the MWC user's apparent mass was represented by a rigid body with one or two degrees of freedom as proposed by Wei and Griffin [74]. However, the two models used to represent the MWC user's apparent mass did not accurately predict the seat vibration transmissibility during the simulated road course test (both overestimated the seat transmissibility).

Vansickle et al. [75] developed a model of the transfer function between the MWC frame and the participant's head. This approach evaluated the participant's head acceleration from the acceleration on the MWC frame, with no need for anthropometric data. However, the coefficients of the transfer function needed to be calculated a priori and were obtained by an identification procedure based on the minimization of the error between the calculated and the experimental head acceleration. This model could be used on MWC users and able-bodied participants for 10 cm curb descent, but not for the 10 cm curb ascend and the bump.

Moreover, one article presented in the present review developed a model of an isolated MWC. This article [50] forwarded a finite element model (FEM) of an isolated MWC by dividing it into seven parts: Tire, rear frame, front frame, armrest, seat, footrest, and handle. This FEM model was validated by comparing the outputs to the eigenfrequencies obtained during experimental modal analysis. Skendraoui et al. [39] plan to use this model to study structural fatigue and to identify points of reinforcement in the MWC.

4. Discussion

4.1. General Observations

This article reports a synthesis of the current knowledge regarding vibration transmissibility during MWC propulsion. After article identification and a selection procedure based on PRISMA recommendations, 35 articles were considered. This review identified three main fields of study: The vibration content, the parameters affecting vibration transmission, and the modeling of vibration transmission.

The present review underlined that real daily-life conditions have little been investigated, and therefore, are not known enough to understand real MWC behavior. Only two studies reported data from real daily-life measurements [30,45]. This limited amount of information is consistent regardless of the field of application (e.g., vibration exposure while riding or driving a vehicle). The most likely reason for this limitation is the technical difficulty of conducting vibration measurements in a real daily-life situation. Such an experiment requires wireless, lightweight, and accurate sensors that have only become available in recent years [76]. To deal with these difficulties, many studies have carried out experiments on a simulated road course to reproduce the different floors and obstacles encountered by MWC users every day [31,40,67]. However, a simulated road course is a sequence of short displacements that focus on classical daily difficulties. As a result, the duration of exposure (approximately 30 s [40]) is shorter than the actual daily duration of propulsion for MWC users (approximately 2 h [45]). Similarly, the time spent on each obstacle encountered during a simulated road course is not representative of a real daily life course. Therefore, to better replicate real daily life, the amount of vibration on each obstacle needs to be weighed by the time and/or the occurrence of each obstacle over several days. For that purpose, a preliminary investigation needs to be performed to identify the frequency occurrence of each situation during a typical day.

Most of the articles presented an experimental procedure based on the ISO 2631 standard [21], which is suited to studying vibration exposure in AB people resulting from involuntary movements. Nevertheless, this standard is not the best framework to investigate MWC users' exposition to vibration. Some studies underlined the limits of using a standard developed for non-voluntary motions on MWC users propelling an MWC, since the voluntary motion was shown to affect the vibration transmissions through the body [22,77]. The use of the ISO 2631 standard is even more inappropriate as no article complied with all of its recommendations. For instance, the time of exposure (e.g., less than 1 min of measurement [41,51]) was shorter than the real duration of real daily life conditions (e.g., around 2 h of movement distributed over 13 h on the MWC [45]). In addition to that, the amount of vibration on the footrest and the backrest were neglected to represent the total amount of vibration received by the MWC user [45]. Moreover, the 60 Hz sampling rate used in this study [45] was too low to quantify the amount of vibration over the range of frequencies affecting human health and comfort (0–80 Hz [21]). This limitation was, however, due to experimental constraints: As data were acquired during several days, a low sample rate was used to ensure data storage capacity.

Regarding the studied population, most of the articles reported studies carried out on AB participants. Conducting experiments on such a population is easier than on MWC users, especially for ethical reasons and safety procedures. However, the results carried out with AB participants might be questionable because MWC users, due to their pathology, have specific muscular control, posture, or propulsion technique that are likely to affect vibration transmission [68,69]. Hence, it would be beneficial for the scientific community to ascertain the similarities and differences between AB and MWC user populations. This would enable more carefulness and understanding when studying results from AB people, without completely rejecting them. Regardless of the participants' population, their anthropometrical characteristics could also affect vibration transmission. From mechanical principles, the mass of the participant should influence the amount of vibration. Vibrations at higher frequencies are expected for lighter users. Experimentally, such a conclusion on the influence of participant's mass was not observed [39,64]. However, in these studies, the experimental design also included additional differences between the participants: Dummies with structural difference [64] or participants that may have a different posture or muscular control [39] that also affected vibration properties [69]. To better understand the effect of the MWC users' characteristics (e.g., posture, weight) on vibration transmissibility, further studies are required because the apparent mass is mainly observed to study human vibration [78], but in none of the articles considered in this systematic review.

Because they need to address specific demands relative to their associated sport, sport MWC design can differ noticeably from daily life MWC. In sports that need high maneuverability (e.g., tennis, basket), the wheel camber is usually higher. In other sports (e.g., racing), the MWC frame is longer to decrease rolling resistance, while increasing stability. Additionally, a protective horizontal bar can be added to the frame for some sports (e.g., basket and rugby MWC) to protect users from a collision, due to omnipresent contacts between MWC [79,80]. These repetitive contacts between MWC generate shock properties that are not observed under real daily-life conditions. Moreover, almost all of the articles have only considered daily-life propulsion speeds, whereas higher speed increases the number of sustained vibrations [52,61]. While many differences exist between sport and regular MWC usages, there is only one article considering sport MWC [36]. Therefore, it appears there is still a lack of knowledge of MWC vibration transmissibility during MWC-based sports activities, which required specific studies. Because both MWC frame and rolling surface depend largely on sports, specific studies would probably be required for each sport of interest.

Not only did this review display the diversity of experimental procedures, but it also highlighted that both processing methods and computed parameters greatly vary from one study to another. Consequently, a clear evidence-based synthesis was difficult to draw since each outcome is highly dependent on methods and parameters. As an example, DiGiovine et al. [40] drew opposite conclusions using parameters extracted from the weighted and unweighted signals. Although investigating unweighted signals is relevant to the effect of vibration on the MWC structure, weighted signals are more relevant to study the human body [40]. Hence, it appeared noteworthy to define a straightforward framework to conduct studies on the MWC users' exposition to vibrations.

4.2. Vibration Content Reaching the Human Body

Despite the complexity of framework definition and the great variety of detailed results, all the reviewed articles state that MWC users are overexposed to vibration in a frequency range known as deleterious for the human body (4–12 Hz [21]). MWC users are exposed to vibration, but they also undergo shocks from curbs' crossing or other obstacles causing high amplitude accelerations [45]. The current environmental conditions put MWC users in extreme conditions. The amplitude of the head vibration was lower during drum shock simulator experiments than during curbs descents [52,53]. Even if the drum shock simulator is the method commonly used for MWC frame mechanical fatigue test [65,81]. Moreover, as shock amplitude increased with curb height [43,50], it might be interesting to decrease the height of the curb by combining the curb with a slope. On top of that, floors are usually not optimized to be ridden on and negotiated with an MWC. The most used floor (poured concrete) is the one that induces the highest amount of vibration at the seat [46,48,49]. Regardless of the field, articles observed an increase in the amount of vibration with the floor's roughness and aging [44,48,49,82,83]. However, no study has tried to predict the amount of vibration in the MWC combining the effects of both floor roughness and speed. This combination was studied in the context of bicycle rides. Chiementin et al. [84] developed an equation providing the vibration input frequency from both the bicycle speed and the paving stone's characteristics. Such a prediction could be useful to dimension MWC or as input information for an MWC/users vibration transmissibility model. To counteract these harmful effects, modifying pedestrian pathways might not be the easiest solution, since it would require important means. Therefore, improving the MWC or a specific element's response to shock and vibration would probably be a better approach. For this purpose, vibration characteristics induced by the floor, as well as the response of the MWC users to such vibration must be preliminarily determined.

This review also highlighted that the human body has different abilities to absorb vibration and shocks. Contrarily to vibration, shock amplitudes decrease between the seat and the able-bodied participant head [42,56]. This difference did not seem to be caused by the seat cushion, as Garcia-Mendez et al. [54] observed an increase of shock amplitude through the cushion. Therefore, the human body appeared to be more prone to absorb isolated shocks than vibration. Shock-generating events are visible, so the participant probably adjusted his posture and muscle activation to anticipate the shock. As such adjustments affect vibration transmissibility [69], this could explain the difference in the human body's ability to absorb vibrations and shocks. As MWC users could have a specific muscular control, further experiments are required to understand how MWC users can absorb shock depending on their level of disability.

During MWC propulsion, a general agreement established that MWC users are predominantly exposed to vibration along the vertical direction [41]. It is also commonly accepted that vibration amplitude along the mediolateral direction is negligible with respect to the vertical direction [41]. However, the importance of the anteroposterior direction is still under discussion [30,36,40–42]. This is why vibration and shock were generally estimated along the vertical and anteroposterior directions or along the vertical direction only. The importance of the anteroposterior direction can be evaluated by looking at both the studied population and the observed parameters. According to the sensations reported by MWC users [30], the vibration transmissibility between MWC users' heads and their seats was lower in the anteroposterior than in the vertical direction [40]. However, for all of the other observed parameters, the amount of vibration and shock amplitude in the vertical and anteroposterior directions were similar (e.g., 0.4–2 m/s^2 [42]). On the contrary, for cycling, the amount of vibration along the anteroposterior direction (e.g., around 1 m/s^2 [82]) was lower than along the vertical direction (e.g., 3–6 m/s^2 [83]) [18,82]. The anteroposterior movement induced during propulsion may explain such differences.

If vibration exposure when propelling an MWC cannot be entirely avoided, it must be ensured that its properties are not deleterious for the human body. This could be done by shifting deleterious frequency out of the critical bandwidth. For that purpose, characteristics of the deleterious/uncomfortable solicitations have to be determined. Currently, no study identified a deleterious/uncomfortable range of frequencies for MWC users, but only for seated AB (i.e., 4–12 Hz [21]). By considering this bandwidth for MWC users, they are regularly exposed to deleterious frequencies, and the MWC and user couple tend to amplify the vibration in it. Besides, frequencies at which MWC users are exposed agree with MWC users' complaints on certain body parts (i.e., buttock, low back, and neck) [30,57]. Hence, even if not properly proved, vibration exposure may be responsible for some of the second comorbidity risks observed in the MWC population [8].

4.3. MWC Elements

Changing the MWC user's environment to decrease its vibration exposure is rarely possible. Therefore, another way to act on MWC user's vibration exposure could be to improve the MWC geometry and/or material. MWC is composed of many elements that affect the vibration transmission through the structure. However, most of the MWC elements cannot be modified without changing the whole structure, to avoid a straightforward parametric analysis of the effect of each element on vibration exposure. For instance, it was not relevant to study a given MWC with and without suspensions to pinpoint how suspensions affect vibration exposure. Therefore, comparisons had to be performed on two different MWC, e.g., a suspended MWC versus a conventional MWC [50–52]. Using this methodology, the suspensions were observed to be efficient mainly during shock situations (i.e., drum shock simulator, drop, and simulated road course) [50–53,64]. As the Quickie XTR suspended MWC was identified to be the best suspended MWC with respect to other suspended MWC models over different articles [50,53], the spring-damper suspension could be an interesting type of suspension to decrease the amount of vibration. It is also important to notice that the direction of the suspension affects its efficiency. Suspensions are designed to damp vertical shocks [50]; but depending on the situation and the user technique to overcome physical obstacles, MWC tilt can change, and therefore, the shock can occur in a different direction than the suspensions. However, in this same article [50], changes other than the tilt at impact occurred. The authors also compared different MWC suspension types and different curbs heights. Therefore, this hypothesis still needs to be confirmed. Furthermore, studying the tilt of MWC users over different daily situations could help find the optimum MWC suspension angle to improve suspension efficiency. As each MWC user has a specific riding technique, it could be useful to have the ability to tune the angle of rear-wheels suspensions to optimize shock absorption for every individual. While rear-wheel suspensions could decrease shock amplitude, they did not reduce the amount of vibration produced during an MWC propulsion, and they increased MWC mass and cost [51]. As some conventional MWC transmit a lower amount of deleterious vibration than some suspended MWC, suspensions may not be needed [50] and could be offset by a better design of the MWC frame to address the same issues.

On the contrary, castor fork suspension presented more encouraging results for vibration and shock absorption, even if they were only introduced in two articles [37,64]. Nowadays, daily-life MWC is still rarely equipped with castor fork suspensions. One reason could be that only a few MWC manufacturers offer such a suspension system. Another reason could be that the suspension system may absorb a part of the propulsion energy generated by the user, which would constrain MWC users' experience of increasing difficulty to propel the MWC. To avoid vibration induced by the castors, active MWC users usually perform wheelies on obstacles [53].

While the highest vibration values were observed at the footrest [48], no article mentioned footrest improvement to limit vibration transmissibility. It might be related to MWC users' pain locations, which are mainly focused on the upper limb segments rather than on the lower limbs [8,30]. Vibration transmitted by the footrest might also be damped by the user's leg. All of this aside, a deeper focus on this part of the MWC could improve footsupport on the footrest, which is important not only for driving the MWC, but also for limiting the risk of falling.

The effects of wheel type on MWC vibration were sparsely studied. The only article that compared two types of wheels did not observe any difference [61]. For some MWC users, a solid wheel is recommended to prevent the risk of puncture. However, no article studied the effect of such a wheel on the amount of vibration transmitted. Most of the articles used the inflating pressure recommended by the tire manufacturer, but none observed the effect of the pressure on the vibration transmissibility. Nonetheless, maintenance of MWC is often neglected, which results in underinflated tires for many MWC users. The effect of tire inflation studied relatively to motion resistance [85,86], should also be investigated in both vibration and shock absorption. Similarly, MWC frame and wheel materials could be an interesting aspect to investigate, especially due to the number of new composite materials currently developed in industry, such as carbon material, for instance.

To improve comfort and to prevent pressure sores, seat and backrest cushions are usually added. Surprisingly, today, MWC users tend not to use seat or backrest cushions that prevent them the most from vibration transmissibility. Recommendations need to be provided to assist with the cushion choice relative to MWC users' pathology regarding vibration transmissibility [40]. It is even more important that certain seat cushions tend to amplify the amount of vibration [54]. If seat cushions are designed for pressure sores prevention or to provide support to MWC users, vibration maybe a way to decrease the risks of a pressure sore [87]. Moreover, to ensure support capacity, cushions are validated through ISO 16840 standard, which is not fully adapted. Indeed, ISO 16840 experiments consist of a drop of a buttock shape indenter on a cushion resting on a plate. As described before, contrary to shocks, vibration tends to be in the frequency range deleterious for the human body. Cushion material properties should equally be considered. Moreover, vibration transmission through cushions is affected by the surrounding structure (i.e., MWC frame and user). As the material properties of the indenter are not specified in the standard, the chosen material (e.g., lead shot with an epoxy adhesive) in the studies did not seem representative of the human body [65]. Moreover, the plate, on which cushions were set up, might also be unrealistic compared to the vibration properties of the MWC frame. Finally, cushions were considered with only one degree of freedom, which is highly unlikely as some articles have already found between three to five eigenfrequencies for MWC cushions [66,88]. Some cushions transmit less vibration than other cushions. However, the cushions that exhibit lower seat-to-head transmissibility can be different from one user to another. The cushion type with the lowest vibration transmissibility is different from AB participant to MWC users, but also in between different MWC users [40,42]. If the air cushion transmitted less vibration for AB participants, no difference was found between the different cushions investigated amongst MWC users. The most likely reason for such differences between the users is the effect of the cushion on users' stability and support. This is why cushions with gel, due to their viscoelastic properties, have better damping properties than cushions filled with air [65]. For users with full muscular control (i.e., AB), the cushion with the lowest damping properties, which is the cushion filled with foam and air, showed the lowest vibration seat to head transmissibility [40,42]. Another reason could be linked to the participant weight because both the stiffness and the damping properties depend on the cushion preloading [54]; changes of such properties were proven to affect the vibration transmission [63]. Therefore, participant weight may affect the vibration transmission, and as a consequence, the ability of the cushion to absorb vibration.

4.4. Perspective and Limitations

As many parameters affect vibration transmissibility, experimentally determining the MWC that minimizes the most deleterious vibration is complex. On top of that, MWC users' characteristics modify the MWC vibration transmissibility. Hence, the MWC properties that minimize harmful vibration transmissibility could be different between two different MWC users. To answer this issue, the most practical way to identify the most relevant parameters that minimize deleterious vibration would be to simulate the vibration transmissibility through the MWC/users system. However, very few models exist for vibration transmissibility during MWC propulsion. This systematic review reported only six articles describing a model of MWC vibration transmissibility, and all the models developed were two-dimensional models in the sagittal plane. As the amount of vibration was preponderant along the vertical axis and anteroposterior direction, developing a model in the sagittal plane could be sufficient. The most detailed model was proposed by Kawai et al. [38,63]: Each segment of the MWC user was represented, and the three contact points (i.e., footrest, seat, and backrest) between the user and the MWC were considered. MWC users' characteristics (mass and segment length) and their posture could, therefore, be accurately represented. However, as for the other models, the whole MWC was constructed as a single rigid body, thus preventing modification of the MWC properties and settings. Moreover, no model was developed for the MWC during the propelling action, whereas the vibrating properties of the MWC could be different between users between dynamic and resting conditions [22]. Therefore, no model currently exists for estimating vibration transmissibility during MWC propulsion. Such models require numerous parameters (transfer function, damping, and stiffness coefficients), which imply experimental data and expensive numerical simulation. Hence, there is still a massive lack of information regarding the modeling strategy of the MWC/user system. This review article only focused on articles relative to MWC. However, similar rolling systems, such as bicycles, are more studied in dynamic conditions [77,89], and such works could be transposable into the investigation of MWC vibration issues. It could also be useful to observe research pursued in the transportation field. Vibration during different types of transportation is well studied, and models coupling peopleand seats or cars are already widely developed [90].

5. Conclusions

Manual wheelchair (MWC) users are constantly exposed to vibration. It is broadly known today that human body exposure to certain vibrations can be detrimental to health and a source of discomfort and fatigue. Identifying key parameters influencing vibration is, therefore, crucial to better understand how to avoid human health being impacted. For that purpose, a systematic review was realized to synthesize the current knowledge (e.g., amplitude and frequencies description, modeling) regarding vibration transmissibility during MWC propulsion.

This review showed that both methods and parameters currently used to quantify the amount of vibration are varied, and most of the articles limited their investigation to one parameter only. As conclusions could differ between the parameters studied, developing a common method easily reproducible could be useful for any research on MWC vibration transmissibility. Simulated course roads have been proven to be efficient in studying vibration during MWC propulsion. However, a preliminary investigation needs to be performed to identify the frequency occurrence of each obstacle situation during a typical day and be able to correctly analyze the results. Besides, to confirm results obtained from able-bodied experiments, it will be interesting to ascertain clear similarities and differences between AB and MWC user populations. Despite the heterogeneity of the methods used, all of the articles reported that MWC users are over-exposed to vibration on the frequency range deleterious for a seated human body. Moreover, the frequency of vibration at which MWC are exposed tends to match the resonant frequency of the MWC user's painful body parts. If shocks are absorbed by the participant body, studies highlighted that the vibrations are not and tend to be amplified by both the MWC and the participant. However, the current standard developed for MWC evaluation does not include the vibration criterion.

The analysis of the literature showed that vibration induced by MWC propulsion could be affected by many parameters relative to the MWC system (e.g., MWC design, material, suspensions, and cushion), but also by parameters external to the MWC (e.g., environment and participant characteristics and propulsion technique). Currently, the external environment is not adapted to the MWC, nor is the MWC optimized for the users. The seat and the backrest cushions used by MWC users are not reducing the vibration transmissibility at their minimum. Recommendations need to be standardized to assist physicians in the choice of cushion type relative to MWC users' pathology. As many factors can affect vibrations, conclusions on the influence of each MWC element are still difficult to assess. Nevertheless, the suspensions do not seem to be a good option to decrease the amount of vibration transmitted to the human body. Further studies are needed to conclude on the effects of other parameters, such as the frame, the wheels, and the footrest, on the vibration content.

Furthermore, each MWC user has a specific tolerance toward the same amount of vibration received. Therefore, MWC settings or components that are appropriate for one MWC user, could not for another. Because the testing process is time-consuming, due to the number of factors and the number of possibilities, a numerical simulation shortcuts the identification of the best MWC settings and parameters for its user. Currently, only a few models exist to model vibration transmission during MWC propulsion, and only one model considered both the MWC and the user for its vibration analysis. Unfortunately, this model associated the MWC with a rigid body making the effect of a change in components or MWC configuration impossible to study. Moreover, no model was developed under propulsion conditions. Therefore, current models need to be improved to fit all the expectations described above.

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Appendix A

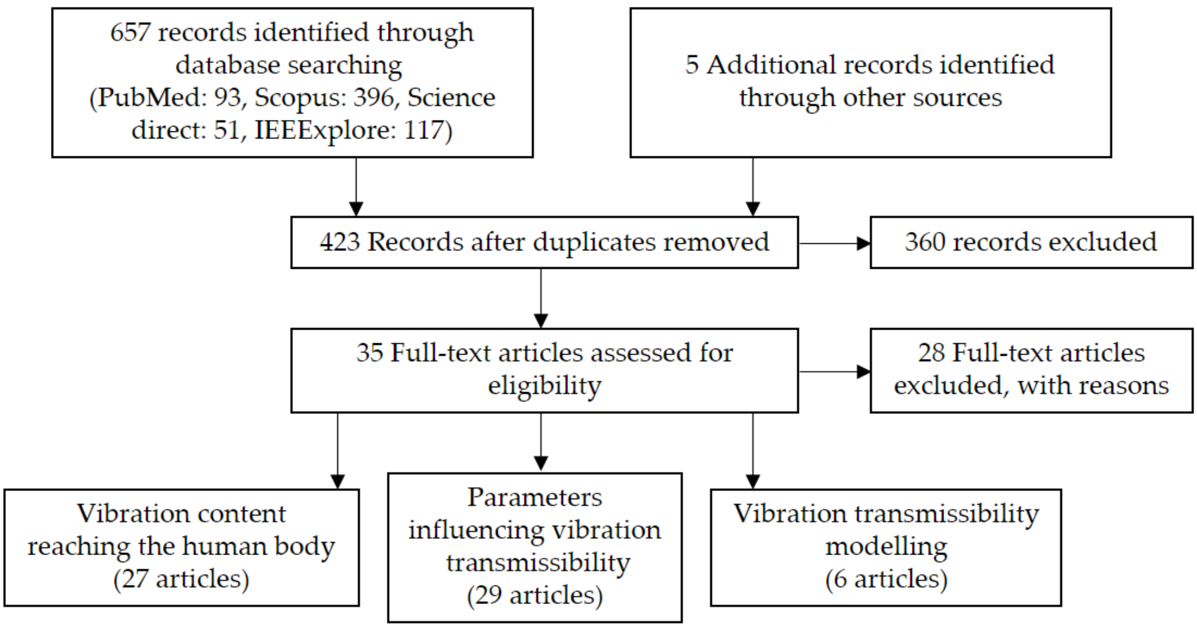

Figure 1. PRISMA flow diagram presented article selection [34].

Appendix B

The international standard organization (ISO), through the ISO 2631, developed guidelines to prevent health risks, due to shock and vibration at work. To estimate vibration parameters with the ISO 2631 method, first of all, weighting coefficients are applied to each octave between 0 and 80 Hz of the temporal acceleration measured (a_i) using,

$$a_w = \left[\sum_i (w_i a_i)2\right]^{\frac{1}{2}}, \tag{A1}$$

where the weighted coefficients (w_i) values are given by the ISO 2631 guidelines and depend on the posture, point of measurement, and vibration negative effect (health, comfort, perception, or motion sickness) studied. The objective of these coefficients is to give more importance to vibration frequencies deleterious for the seated human body.

The effective value of the weighted acceleration (a-RMS_i) shall be next calculated for each axis *i* as,

$$w\text{–}RMS_i = \left[\frac{1}{T}\int_0^T a_w^2(t)dt\right]^{\frac{1}{2}}, \tag{A2}$$

where T is the time of exposure and $a_w(t)$ is the weighted acceleration.

In the case of exposition on shock, ISO 2631 standard also recommend calculating the vibration dose value for each axis *i* (VDV_i), which is more sensitive to the acceleration peaks. *VDV* is represented as,

$$VDV_i = \left[\int_0^T a_w^4(t)dt\right]^{\frac{1}{4}}. \tag{A3}$$

Finally, *w-RMS* (resp. *VDV*) is calculated by,

$$w\text{–}RMS = \left[\sum_i (K_i \times a\text{–}RMS_i)2\right]^{\frac{1}{2}}, \tag{A4}$$

which is the root square of the sum of the squared $a\text{-}RMS_i$ (resp. VDV_i) value for each axis *i* weighted by a coefficient K_i Coefficients are provided by the ISO 2631-1 standard and depend on the posture and measurement point.

Appendix C

The international standard organization (ISO), through the ISO 16840-2, developed guidelines to determine the physical and mechanical characteristics of the seat cushion. This guideline is divided into two experiments: the first one to identified friction properties of the cushion; and the second one to quantify shock absorption under normal loading conditions. The second experiment determines the ability of the cushion to reduce impact loading on tissues and help maintain postural stability. After preconditioning the cushion, the cushion is placed on a rigid platform inclined to 10° with human anatomy shape indenter plan. The dimensions of the indenter depended on the cushions and were provided in the ISO standard. Its weight is about 500 N. The accelerometer is fixed to the top surface of the indenter, on the centerline, at 127 mm forward of the rear edge to record the acceleration during the drop and the rebound. This experiment needs to be done three times. To quantify the ability of the cushion to absorb shock, the ratio between the amplitude mean of the initial impact and the second impact is calculated as a percentage.

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