Inducing Self-Motion Sensations with Haptic Feedback: State-of-the-Art and Perspectives on “Haptic Motion”

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***Abstract*—While virtual reality applications flourish, there is a growing need for technological solutions to induce compelling self-motion, as an alternative to cumbersome motion platforms. Haptic devices target the sense of touch, yet more and more researchers managed to address the sense of motion by means of specific and localized haptic stimulations. This innovative approach constitutes a specific paradigm that can be called "haptic motion". This paper aims to introduce, formalize, survey and discuss this relatively new research field. First, we summarize some core concepts of self-motion perception, and propose a definition of the haptic motion approach based on three criteria. Then, we present a summary of existing related literature, from which we formulate and discuss three research problems that we estimate key for the development of the field: the rationale to design a proper haptic stimulus, the methods to evaluate and characterize self-motion sensations, and the usage of multimodal motion cues.**

***Index Terms*—Haptic motion, self-body motion, haptic rendering, vection, virtual motion, motion platform.**

I. Introduction

VIRTUAL reality (VR) has gone through considerable development over the last years, with an impressive improvement of both auditory and visual rendering techniques. Regardless of the quality and sophistication of audiovisual technologies, they cannot help a lack of body sensations, because the efficient production of bodily effects often requires other modalities than vision and hearing.

Motion platforms constitute the canonical technology to provide self-motion sensations to a user. They rotate or translate the seat or cockpit in order to provide both real and illusory motion, be it realistic or emotionally impacting. Initially applied to flight training devices (see [42] for a historical review), their usage extended progressively to other fields over the last fifty years: drive simulators from the 1970s, arcade deluxe cabinets and theme park simulated rides from the mid-1980s, 4D movies from the 2000s and finally VR motion theaters from the mid 2010s.

On another note, haptic technologies drew considerable attention in the field of virtual reality, building strong industrial tension in the huge market of video games. They provide either tactile cues (through the skin) or kinesthetic cues (through muscular and ligamentous load), and are therefore extremely diversified in their functioning and effects. Yet, their main goal is usually to simulate physical interactions with virtual objects.

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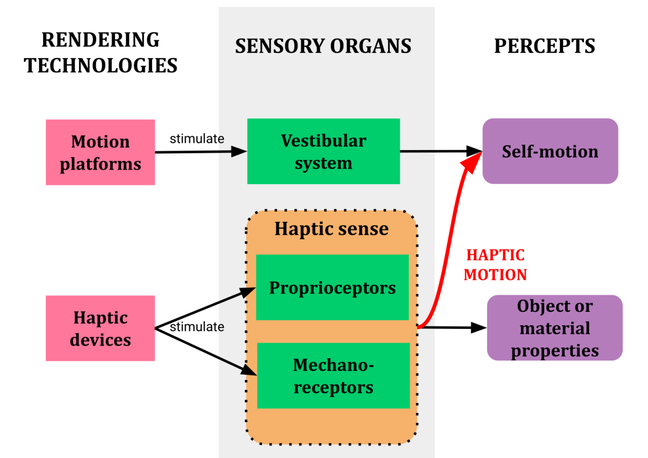

Fig. 1. Self-motion sensations are usually induced by means of a motion platform displacing the whole body. The use of local haptic stimulation to simulate self-motion (instead of physical contacts with the virtual environment) constitutes an emergent approach, that we define as "haptic motion".

In the last decade, a variety of research works explored a new approach: achieving motion rendering (that is usually performed by motion platforms) by means of various localized haptic stimuli. This approach, which can be called "haptic motion", constitutes a ground-breaking change in the usage history of haptic devices, shifting their target from the sense of touch to the sense of motion. We propose to define it more formally as the use of a haptic stimulation that:

- targets specific haptic mechanoreceptors
- is responsive to the simulated virtual self-motion
- is meant to induce or enhance the user's illusory self-motion.

Kooijman et al. provided an in-depth review of illusory self-motion enhancement techniques by means of tactile stimulation [23]. They provided a thorough discussion on vibrotactile and airflow stimulation techniques, the various target body locations, and the impact of cross-modal interactions. We aim to deepen and extend their work, notably by including the use of force-feedback devices, and the discussion of self-motion evaluation methods.

In this paper, we strive to introduce and formalize the haptic motion paradigm, to review current status of research and to discuss the challenges remaining for this research field. We first summarize some key notions about the sense of motion in virtual environments, and define the haptic motion approach. We then review haptic motion literature, and classify it according to the modality and the target body location of the haptic stimulation. From this survey, we formulate and discuss three main research problems for the community: how to design the haptic stimulus, how to evaluate the results, and how to deal with multimodal stimulation. We suggest guidelines for future research, and finally discuss the scope delineated by our formalization.

II. Fundamental notions of haptic motion

In this section, we summarize basic notions about self-motion perception in virtual environments and illusory self-motion techniques, and introduce the concept of “haptic motion”, highlighting its specificities compared to other haptic rendering approaches.

A. The sense of motion in virtual environments

Multiple modalities contribute to the perception and control of self-motion [3]. The visual system, the vestibular system of the inner ear, the somatosensory system of cutaneous receptors, the proprioceptive system of muscle and joint receptors, as well as the auditory system can be involved. Modeling self-motion perception remains a distant scientific challenge, yet it is well established that contributions from all relevant senses are perpetually combined in a subtle and complex processing distributed through the nervous system, to produce conscious perceptions as well unconscious mechanisms like muscle coordination [12]. This powerful ability may be misled in particular circumstances: we then experience a self-motion illusion [35].

B. Virtual self-motion and illusory self-motion

Although virtual reality devices aim to reproduce body displacement (and eventually walking) realistically, their main benefit is precisely to provide a *virtual* experience, and *virtual self-motion* allows the body to stay safely in place while the user is virtually driving, flying, jumping, falling, swimming, or floating into space. Ideally, virtual self-motion should lead to illusory self-motion in order to ensure comfort and presence.

Illusory self-motion is often called “vection” in the literature, a term that arises from the early study of visual illusions, as it is quite easily triggered with a consistent optic flow [11]. The meaning of “vection” may vary among authors, and changed throughout history towards a more general idea of illusory motion awareness [31]. For the sake of clarity, we will prefer the term of “illusory self-motion”, referring to any feeling of one’s own body displacement that is different than the actual physical motion.

Cybersickness, or VR sickness, is the other main phenomenon occurring when moving in a virtual environment. It is a set of uneasing symptoms similar to motion sickness [10]. Cybersickness being a major issue to the development of VR applications, there is a huge research effort to understand, predict and mitigate cybersickness effects [33]. There has been a persistent scientific debate on the relationship between illusory self-motion and cybersickness, which is still challenging to establish [34]. Nevertheless, illusory self-motion is usually considered as a strong correlate of presence, and there is strong evidence that cybersickness can be induced without illusory self-motion [36].

Self-motion illusions are influenced by the properties of the physical stimuli (bottom-up factors). For instance the movement speed of the stimulus, the area of the visual field occupied by the display, or the perceived depth structure of the visual stimulus may influence the onset time, duration, or intensity of the self-motion illusion [11]. But perceiver’s expectations to, and interpretation of, the stimuli also impact self-motion illusions (top-down factors) [27]. For instance, illusory self-motion onset time can be shorter when standing or seating on a structure which is known as being able to move [26].

Techniques producing illusory self-motion are known and studied since at least half a century [32]. “Vection research” historically focused on visually-mediated illusion, but self-motion illusions can be produced by independent or combined visual, auditory, haptokinetic, biomechanical or vestibular stimulation [31]. This is the core idea of “haptic motion”: take advantage of this diversity of perceptual phenomena to achieve *motion rendering* with haptic rendering technology.

C. What is haptic motion?

The term “haptic motion” was first coined by Ouarti et al. [13] who presented an innovative approach to enhance illusory self-motion. Rather than moving the whole body, they suggested to use a force-feedback handle, providing motion cues on the hands only. In contrast with traditional force-feedback simulations displaying physical contacts with the environment, their haptic feedback was reflecting the user’s virtual motion. That is, instead of addressing the perception of touch, the force feedback addressed the perception of self-motion.

We propose to formalize this approach more generally, as the conjunction of the three following criteria:

1) The haptic stimulus targets some of the mechanoreceptors dedicated to the haptic sense: it is applied on specific parts of the body, eventually with various devices. This devices might actuate directly the body, or actuate a rigid intermediate like the seat or floor, or even reach the user through airflow. They might make use of various modalities like vibrations, forces or skin stretch.

2) The haptic stimulus is responsive to the simulated self-motion: it provides a haptic metaphor reflecting, directly or indirectly, the user’s virtual self-motion. It may replicate the vehicle’s vibrations, the step impacts, or the wind on the user’s face. Just like motion platforms considerably filter and transform the simulated motion signal to fit inside their workspace constraints, the stimulation is adapted to the chosen rendering device and modality. In the context of a real-time environment (e.g. video game, VR app), the virtual self-motion can simply be provided by the software engine. In the context of a 4D movie, the motion content can be either recorded from a shooting set or manually authored during post-production phase (see Figure 2), or eventually extracted from the visual content [37].

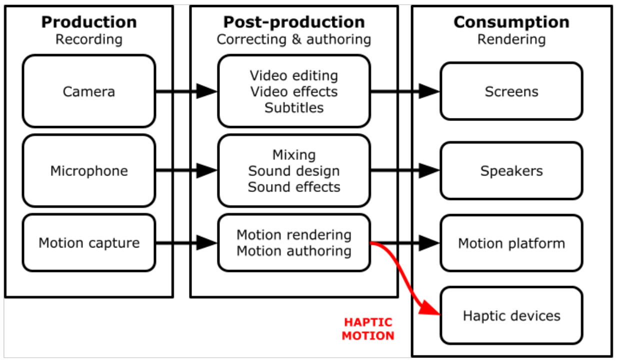

Fig. 2. Haptic motion within the 4D cinema production workflow. Just like sound, motion information can be either recorded or authored in post-production. Haptic devices can be used in replacement or complement of motion platforms.

3) The haptic stimulus is meant to induce or enhance the user's illusory self-motion: In practice, haptic motion usually aims to enhance an existing audiovisual content that already contains self-motion. The additional haptic stimulation should significantly increase the subjective intensity, realism and/or comfort of the self-motion sensations. In some cases, the simulation does not include visual and/or audio content, or it does not include explicit motion (e.g. being in a virtual elevator with no opening): in this case the haptic stimulation should induce self-motion sensations (e.g. noticing that the elevator is moving up).

D. What is not haptic motion?

Haptic motion can be seen as a specific paradigm of haptic feedback, alongside the classical paradigms of physical contact and texture rendering, haptic navigation assistance or haptic communication. In this subsection, we detail how to differentiate haptic motion from other haptic approaches.

1) The haptic stimulation is applied on specific parts of the body: therefore motion platforms, which move the whole body, are not part of haptic motion. Also, a haptic motion stimulus targets receptors dedicated to touch, therefore galvanic vestibular stimulation techniques (which target vestibular signals) are not part of haptic motion.

2) The haptic stimulation is responsive to the simulated virtual self-motion: therefore traditional haptic rendering based on object properties and relative positioning, as well as haptic communication systems, are not part of haptic motion.

3) The haptic stimulation is meant to induce or enhance the user's illusory self-motion: this excludes haptic communication systems, motor rehabilitation applications, redirected locomotion and navigational guidance technologies. Also, eliciting a haptic illusion (like the cutaneous rabbit or funneling illusion) is not a sufficient condition. A haptic motion system should have a significant impact on illusory self-motion, leading to more intensity, realism and/or comfort.

III. State of the Art

In this section, we review current literature on haptic motion. In accordance with the three criteria detailed in Section II-C, we did not include the studies involving a non-localized or non motion-related haptic stimulus, and/or not evaluating the impact on perceived self-motion. We classified the results according to the modality used and the targeted body location. The results are grouped in Table I.

The present work extends the one by Kooijman et al. [23]: we included 22 of the 24 papers they surveyed, removing one duplicate entry by Matsuda et al., and the work by Rupert and Kolev which did not include a control condition for evaluating the self-motion sensations. In addition, we included 1 paper (2 experiments) involving airflow, 2 papers involving vibrational tactile flow and 6 papers (7 experiments) involving force or torque feedback devices, for a total of 33 experiments. In the following, we arranged them according to the modality of the haptic stimulus, and the stimulated body location.

One particular case is the one of Murovec et al., who implemented a passive digital sliding stimulus with a "foam ring" rotating around the seated user [60]. They did not find any significant impact of those tactile cues on illusory self-rotation, although they seemed to improve the effect of visual and/or auditory cues when presented together.

A. Haptic motion based on vibrotactile feedback

As previously argued by Kooijman et al., vibrotactile devices constitute a hardware of choice to enhance illusory motion. Vibrators are a well-known technology, relatively cheap and easy to implement in various setups. It is arguably the most convenient technology to compare different body locations for a given haptic stimulus, and is especially suited to stimulate the feet, which according to Kooijman et al. provide better results than other body locations.

Some authors used a "tactile flow" metaphor, i.e. designed a stimulus distributed on several actuators in order to reflect the directionality and the speed of the virtual motion. Others chose to reproduce vibrations induced by the simulated motion (like the humming of the vehicle seat or the step impact on the foot), which we call a "congruent vibrations" metaphor. Those two approaches are discussed in more details in Section IV-A1.

a) Actuating the seat: Simply vibrating the user's seat simultaneously to visual or auditory virtual motion was found to enhance the resulting linear or circular illusory self-motion in several studies. Riecke et al. showed that 15-90Hz vibrations applied to the chair reduced onset time and improved convincingness of the visually-induced self-motion of a rotating panoramic view [24]. Väljamäe et al. found that a 40Hz engine-like vibrations fed to shakers under the chair enhanced both the intensity and the convincingness of the auditory-induced translational illusory self-motion of blindfolded subjects [25]. Riecke et al. showed that rotational auditory-induced self-motion sensations can be enhanced with a synchronized 7Hz vibration applied to the suspended chair accommodating blindfolded subjects [15].

Some studies investigated the use of a vibrotactile seat to enhance self-motion sensations without significant effect. Väljamäe et al. studied auditory induced illusory self-motion coupled with a low-frequency vibrating seat [55]. Amemiya et al. combined tactile flow on the buttock with a virtual racing

Fig. 3. Haptic motion based on vibrators. Left: Vibrators distributed on the chair enhance the perceived self-motion intensity of a virtual train journey [9]. Middle: an abstract directionless vibration applied at the foot sole can induce directional illusory self-motion [28]. Right: Multi-actuator foot haptics system increases perceived self-motion during VR locomotion [21].

game [6]. D'Amour et al. examined the effect of airflow and seat vibration on motion sickness, and found that when used together they reduced self-motion sensations [58]. Soave et al. (Figure 3, left) embedded actuators in a chair and found that vibrotactile stimulation derived from the scene sounds improved the self-motion sensations induced by a VR train scene (statistical significance was not provided) [9].

b) Actuating the feet: Feet appear to be a prime body location in haptic motion studies. Each author used their own technical setup, using one to nine actuators by foot, as well as a variety of vibrotactile and visual stimuli. Nilsson et al. and Nordhal et al. (Figure 3, middle) applied a 50 Hz vibration to transducers embedded in the sole of sandals and presented motionless virtual scenes through a head-mounted display (HMD) [5], [28]. They could successively induce an illusory self-motion which direction and amplitude were largely determined by the visual context. Feng et al. studied the use of multi-sensory feedback, including vibrating the feet, to improve the user experience of walking in a virtual environment [59]. The vibrotactile stimulation had a significant positive effect on both realism and "walking" sensation. Hayashizaki et al. and Kitazaki et al. used a low-pass filtered footstep sound applied to slippers' sole and synchronized with a first-person stereo camera recording of a walk to enhance self-motion and walking sensations [21], [44], [46]. In the latter study, they used 2 vibrators (one under the heel and one under the forefront) and applied a slight offset between the two stimuli. Kruijff et al. (Figure 3, right) used a sophisticated system of eight vibrotactors and one bass-shaker per foot, simulating the roll-off pressure distribution of walking while navigating in a virtual environment, increasing the self-motion sensation [43]. Matsuda et al. applied a footstep sound to a pair of vibrators located under the heel and the forefront with a temporal offset, during a virtual walk presented through a HMD [45]. They showed that both self-motion and walking sensations were significantly improved.

c) Actuating other body parts: Several other works experimented the vibrotactile stimulation of other body parts, but to our knowledge, none of them demonstrated a positive effect on self-motion sensations.

Van Doorn et al. applied tactile flow on the finger while exposing the observer to a radial optic flow [22]. Lind et al. experimented the use of both constant and dynamic vibrations in a virtual reality sandboarding experience [56]. The subject was laying on an actuated wooden board, and thus received vibrations on the front face of the body. Tinga et al. provided rotating tactile flow on the waist to walking blindfolded participants [57]. Enhanced vection was reported by 20% of the participants, suggesting that the effect of vibrotactile stimulation might depend on individual sensitivity.

B. Haptic motion based on force feedback

The use of force (and torque) feedback was also explored, to a lesser extent. Compared to vibrotactile stimulation, force feedback is able to produce actual motion of a body part. The force can be displayed at various locations on the body: the hand (as it is especially mobile and sensitive), the contact areas with the chair (as a vehicle's acceleration is transmitted by the pressure variation on this region), or the head (as it hosts the vestibular system).

From 2017, the haptic stimulation of the head raised interest in the VR community and many prototypes were proposed [1], [2], [29], [30], [39], [47]–[53]. However those papers did not study self-motion perception but rather aimed to enhance user experience in proof-of-concept demo applications. Therefore we did not include them on our survey, although those devices could back up haptic motion studies.

Force feedback was used on the body to reflect either 1 Degree of Freedom (DoF) velocity, 1-DoF acceleration or 3-DoF acceleration, eventually with an inverted direction (see Section IV-A2). Torque feedback was used on the chair to simulate sudden changes in acceleration.

a) Actuating the body: Danieau et al. (Figure 4, far left) proposed to affix three 3-DoF force-feedback devices to a chair in order to stimulate both hands and head and achieve 6-DoF effects [16]. Both rendering models significantly increased the quality of experience compared to the random and no-haptic conditions. Ouarti et al. showed that reflecting virtual acceleration through a 6-DoF force-feedback handle could improve duration and occurrence of visually-induced illusory self-motion for linear and curved trajectories [13]. They found that mimicking acceleration was significantly

TABLE I
SUMMARY OF EXPERIMENTAL RESULTS ON HAPTIC MOTION.

Reference	Haptic Stimulus				Visual stimulus	Auditory stimulus	Evaluation	
	Modality	**Metaphor**	**Location**	**Features**			**Measurement**	**Outcome**
Riecke, 2005 [24] (Exp. 3)	Vibrations	Congruent (constant)	Seat and floor	15-90 Hz	Screen: rotation Panoramic photography	None Noise-canceling headphones	**Onset, Build-up time**: Joystick **Intensity**: Joystick **Convincingness**: rating (0- 100)	**POS** **NULL** **POS**
Väljamäe, 2006 [25]	Vibrations	Congruent (dynamic)	Seat and floor	40 Hz	None	Translation Moving landmarks/anchors	**Intensity**: rating (0-100) **Convincingness**: rating (0-100)	**POS** **NULL**
Riecke, 2009 [15] (Exp. 1)	Vibrations	Congruent (constant)	Suspended seat	7 Hz	None	Rotation Binaural recordings Noise-canceling headphones	**Occurence, Onset**: verbal **Intensity**: verbal rating (0-100%) **Realism**: verbal rating (0-100%)	**POS** **POS** **POS**
Väljamäe, 2009 [55]	Vibrations	Congruent (dynamic)	Seat and floor	10-15 Hz	None	Rotation Moving landmarks	**Onset**:verbal **Intensity**: verbal rating (0-100) **Convincingness**: verbal rating (0-100)	**NULL** **NULL** **NULL**
Nordahl, 2012 [28]	Vibrations	Congruent (constant)	Foot (4 points)	50 Hz noise / sawtooth / both	HMD: motionless Virtual lift	None Constant elevator sound	**Onset**: Verbal **Compellingness**: verbal rating (0-5) **Intensity**: verbal distance	**NULL** **POS** **POS**
Nilsson, 2012 [5]	Vibrations	Congruent (constant)	Foot (4 points)	50 Hz sawtooth	HMD: motionless Virtual lift / train / bathroom / darkness	None Constant fan sound	**Onset, Direction**: Verbal **Intensity**: Verbal distance **Compellingness**: verbal rating (0-5)	no control condition
Van Doorn, 2012 [22]	Vibrations	Tactile flow	Finger	$\sim$ 2 cm/s	HMD: translation Point cloud	None	**Onset, Duration, Latency**: Button **Vection strength**: rating (0-100)	**NULL** **NULL**
Farkhatdinov, 2013 [20]	Vibrations	Congruent (constant)	Foot (footrest)	70-110 Hz sinus / pink noise / chirp	Screen: translation Point cloud	Sound isolation headset	**Intensity**: 2AFC **Onset**: Button	**POS** **POS**
Amemiya, 2013 [6]	Vibrations	Tactile flow	Seat (bottom)	50 Hz - 200 ms 3 speeds / no / random	Screen: translation Racing game, point cloud	None Sound isolation headset	**Velocity**: magnitude estimation (N.S.)	**NULL**
Hayashizaki, 2015 [44]	Vibrations	Congruent (step impact)	Foot	Low-pass filtered footstep sound	HMD: walking Stereoscopic recording	**N.D.**	**Vection**: rating (0-100) **Walk**: rating (0-100)	**POS** **POS**
Kitazaki, 2016 [46]	Vibrations	Congruent (step impact)	Foot (heel)	Low-pass filtered footstep sound	HMD: walking Stereoscopic recording	None	**Vection**: VAS (0-100) **Walking**: VAS (0-100)	**POS** **POS**
Amemiya, 2016 [19]	Vibrations	Tactile flow	Seat (bottom)	50 Hz - 200 ms 5 speeds / no / random	Translation Point cloud (screen)	None Earmuffs	**Velocity**: magnitude estimation (N.S.)	**NULL**
Feng, 2016 [59] (Exp. 1)	Vibrations + Airflow	Congruent (step impact) Air Resistance	Foot (floor) Whole body	Low-pass filtered footstep sound 0-4 m/s at 50cm	HMD: VR locomotion	None Noise-cancelling headset	**Movement**: rating (1-6) **Walking**: rating (1-6) **Realism**: rating (1-6)	**POS** **POS** **POS**
Lind, 2016 [56]	Vibrations	Congruent (constant / dynamic)	Front of body	Constant: 75 Hz Dynamic: 20-100 Hz	HMD: VR sandboarding	None Scene sounds	**Intensity**: rating (0-100) **Compellingness**: rating (0-100)	**NULL** **POS**
Kruijff, 2016 [43]	Vibrations	Congruent (step impact)	Foot (8 points)	Simulation of roll-off pressure	HMD: VR locomotion	Localized footstep sounds	**Self-motion sensation strength**: rating (0-10)	**POS**
D'amour, 2017 [58]	Vibrations + Airflow	Congruent (constant)	Seat + Face and torso	5-200 Hz brown noise 0.9 m/s	Screen: Bicycle ride 1st person video	None Video sounds (street noise)	**Vection intensity**: rating (0-10) **Vection duration**: rating (0-100) **Video realism**: rating (0-10)	**NULL*** **NULL** **NULL**
Tinga, 2018 [57]	Vibrations (walking)	Tactile flow	Waist	308 ms with 154 ms overlap	None	None	**Rotatory self-motion**: rating (0-5)	**NULL**
Kitazaki, 2019 [21]	Vibrations	Congruent (step impact)	Foot (2 points)	Low-pass filtered footstep recording	HMD: walking Stereoscopic recording	None White noise	**Self-motion**: VAS (0-100) **Walking**: VAS (0-100)	**POS** **POS**
Soave, 2020 [9]	Vibrations	Congruent (ambient)	Seat (backrest, bottom)	35-120 Hz Low-pass filtered ambient sounds	HMD: translation Virtual railway tunnel	**N.D.**	**Intensity**: Joystick position	no statistical analysis
Matsuda, 2021 [45]	Vibrations	Congruent (step impact)	Foot (2 points)	foostep sound	HMD: VR walking 1st/3rd person VR	None White noise	**Self-motion**: rating (0-100) **Walking**: rating (0-100)	**POS** **POS**
Danieau, 2012 [16]	Force feedback	3-DoF Acceleration	Head and hands	Direct / Indirect None / Acceleration / Displacement/ Random	Screen: translation / turns / bumps Real and virtual car	**N.D.**	**Feeling of self-motion strength**: rating (1-5) **Consistency with real-world**: rating (1-5)	**POS** **POS**
Ouarti, 2014 [13] (Exp. 1)	Force feedback	1-DoF Acceleration	Hands	Direct	Screen: translation Virtual railway tunnel	**N.D.**	**Onset, Duration, Latency**: Button **Sensation of self-motion**: 2AFC	**POS** **POS**
Ouarti, 2014 [13] (Exp. 2)	Force feedback	3-DoF Acc. / Vel.	Hands	Direct / Indirect	Screen: translation / turns Virtual railway tunnel	**N.D.**	**Sensation of self-motion**: rating (1-7) **Realism**: rating (1-7)	**POS** **POS**
Oishi, 2016 [7] (Exp. 2)	Traction force	1-DoF Velocity	Shoulder	Direct	HMD: translation Racing game	None Noise-canceling headphones	**Acceleration**: rating (1-7) **Speed**: rating (1-7) **Movement**: rating (1-7)	**POS** **NULL** **NULL**
Bouyer, 2017 [17]	Force feedback	1-DoF Acceleration	Hands	Direct / Indirect	Screen: translation Racing game	None	**Realism of movement**: rating (1-7)	**POS**
Rietzler, 2018 [18]	Torque feedback	Acceleration transients	Seat	Short bursts 25 °/s	HMD: translation Racing game	None	**Vection**: rating (1-4) **Acceleration, Braking, Realism**: rating (1-7)	**POS** **POS**
Colley, 2021 [61]	Torque feedback	Acceleration transients + turns	Seat	Short bursts 5-25 °/s	HMD: translation / turns Virtual car	None	**Feeling of self-motion**: rating (1-4) **Realism**: rating (1-4)	**POS** **POS**
Costes, 2021 [8]	Force feedback	1-DoF Acceleration	Head	Direct / Indirect	HMD: translation Cube cloud	None	**Acceleration**: rating (0-5)	**POS**
Seno, 2011 [41]	Airflow	Air resistance	Face	6.37 m/s	Screen: translation Point cloud	None	**Occurence, Latency, Duration**: Button **Strength**: rating (0-100)	**POS** **POS**
Murata, 2014 [38]	Airflow + Sway	Air resistance + body swing	Front, side or back	5.5 m/s 7 cm at 7 cm/s	None	None White noise	**Strength**: verbal rating (0-5) **Occurence**: Verbal	**POS** **POS**
Yahata, 2020 [40] (Exp. 1)	Airflow	Air resistance	Torso	2 m/s 18.6 °C / 35.7 °C	HMD: translation Normal / fire corridor	None White noise	**Magnitude**: verbal rating (0-100) **Onset, Duration**: Button	**POS** **POS**
Yahata, 2020 [40] (Exp. 2)	Airflow	Air resistance (inverted)	Torso	2 m/s 18.6 °C / 35.7 °C	HMD: translation Fire corridor	None White noise	**Magnitude**: verbal rating (0-100) **Onset, Duration**: Button	**POS** **NULL**
Murovec, 2020 [60]	Tactile	Passive sliding	Finger	1-DoF Rotation 45 °/s	Screen: Rotation Panoramic photography	Rotation Stationary objects	**Vection intensity**: verbal rating (0-10) **Vection duration**: verbal rating (0-10)	**NULL** **NULL**

N.D. = Not described. **2AFC** = Two-alternative forced choice. **POS** = The measure was significantly higher in at least one condition with haptic simulation, compared to the control condition (no haptic stimulation or noise). **NULL** = The measure did not change significantly between the control condition and any of the conditions with haptic stimulation. * = A significantly negative effect was found for the condition including both vibratory and airflow stimulation.

more effective than mimicking velocity, and that the direction polarity (direct/indirect mode) had no specific effect. Bouyer et al. (Figure 4, middle left) extended this approach to an interactive video game context, applying the force feedback to a gamepad [17]. They showed that both direct and indirect mode improved the realism of linear acceleration changes. Oishi et al. suggested to pull user's clothes in order to pull the upper body backwards, and attempted to compare acceleration-based, velocity-based and position-based stimuli, with mixed results [7]. Finally, Costes et al. (Figure 4, middle right) experimented applying force feedback at the head with 6-DoF grounded arm, reflecting visual acceleration [8]. In their study both direct and indirect mode led to more intense and more ego-centric self-motion sensations.

b) Actuating the seat: As an alternative to actuating the body directly, Rietzler et al. used a motor and a clutch to actuate a gaming chair along the vertical axis [18]. They found that very short rotational bursts increased self-motion

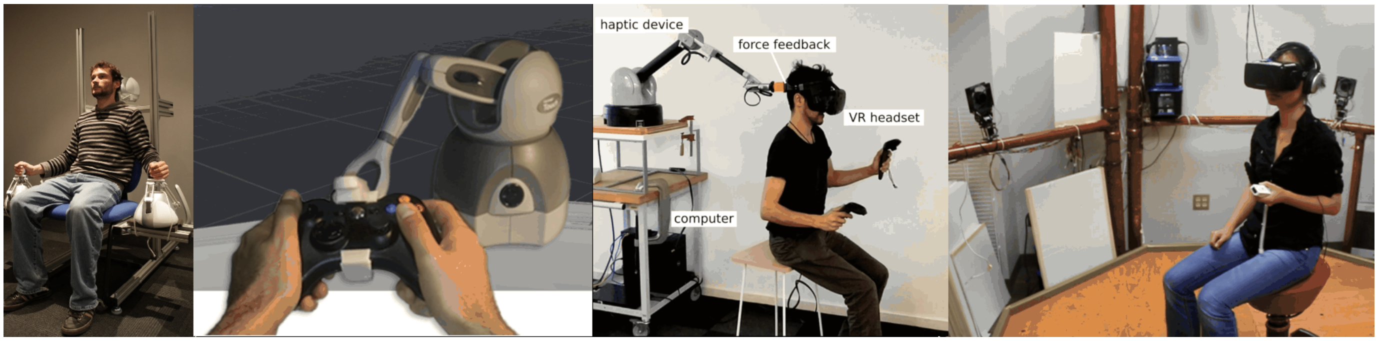

Fig. 4. Haptic motion with force feedback or airflow. Far left: actuating head and hands to provide translational and rotational motion effects [16]. Middle left: actuating a gamepad to enhance a video game experience [17]. Middle right: reflecting visual acceleration with forces at the head to provide more vivid and more ego-centric self-motion sensations [8]. Far right: blowing directional airflow opposed to virtual motion to improve perceived self-motion [59].

sensations in a VR racing game, simulating linear accelerations and decelerations. This stimulus was later used by Colley et al. in an automated car simulation [61]. They extended the technique with the rendering of moderate turns, and also found out a general enhancement of perceived self-motion.

C. Haptic motion based on airflow

Several authors investigated the use of airflow. All experiments but one (Yahata et al., exp. 2) provided a stimulus opposed to the simulated motion, following an "air resistance" metaphor.

Seno et al. used a bladeless fan in front of the subject to enhance the illusory self-motion induced by an expanding optic flow [41]. The effect of the same stimulus on a contracting flow was not significant, confirming the importance of ecological validity. Murata et al. found a a significant interaction on self-motion intensity between airflow and seat sway in the absence of any visual or auditory cues [38]. They used a single fan located either on the front, side, or back of the subject. Feng et al. (Figure 4, far right) used several fans placed around the participant to provide directional wind opposed and proportional to user's speed and significantly enhance self-motion sensations [59]. D'Amour et al. used two lateral fans to blow wind forward, without significant effect except a negative one when combined with vibrations [58]. Yahata et al. provided constant airflow on the torso while moving forward at constant speed in VR corridor, significantly enhancing illusory self-motion magnitude [40]. They compared hot and normal wind, in a virtual corridor either put on fire or not. While in the normal corridor only magnitude was significantly enhanced by both normal and hot air, in the fire corridor only the hot air had a significant effect, but on magnitude, latency and duration. In a second experiment with a backward visual motion (in conflict with airflow direction) in the fire corridor, only hot air improved magnitude, but not latency and duration.

IV. Discussion and perspectives

Haptic motion, understood as the achievement of motion rendering by means of haptic technologies, is a relatively young research field: 23 of the 31 papers we surveyed date from 2013 or later, the oldest one dates back to 2005. Their number roughly doubles every 5 years, showing a growing interest on the topic, yet the scientific achievements remain scattered, and the methods used by the different authors might seem heterogeneous.

In this section, we aim to clarify the possible rationales structuring haptic motion, that could help classify the diversity of approaches and assemble experimental results. From our survey, we identified three challenging research topics for the field that we discuss in the following: the design of a proper haptic metaphor, the methods to evaluate self-motion sensations, and the handling of cross-modal interactions. Finally, we discuss the formalization that we proposed in Section II.

A. Which haptic stimuli for haptic motion?

Motion rendering is traditionally seen as a physical simulation: a motion platform tends to recreate the physical motion as realistically as possible, and the main goal of control laws is to draw on perceptual thresholds to hide the shortcomings of the real motion. With haptic motion, the haptic stimulus is not necessarily motion, and not necessarily "realistic", as long as it produces or enhances sensations of self-motion. Thus, the choice of a proper stimulus and the design of control laws evoking whole-body motion remains an open question. How to represent whole-body motion with vibration? Should an actuated handle reproduce acceleration, speed, or displacement to evoke a virtual ride? From our survey we can draw two main approaches for vibrotactile stimulation (congruent vibrations and tactile flow), and a limited set of metaphors for force feedback, while airflow-based approaches were relatively homogeneous.

1) Vibrotactile feedback: Even though vibratory stimulation is not directional, it was found to be able to increase the self-motion intensity and convincingness ratings. As stated by Väljamäe, it is likely to derive from subjects' prior experience with real vehicles, which usually generate significant non-directional vibrations highly correlated to their motion [25]. In the papers we surveyed, two main strategies are used to modulate self-motion with a vibrotactile stimulus: either providing congruent vibrations evoking "non-stillness" and combining with other cues to suggest motion, or providing a “tactile flow” (sometimes called “apparent tactile motion”) with a perceivable speed and/or direction.

a) Congruent vibrations: The first approach, that we propose to name “congruent vibrations”, consists in synchronizing the intensity of the vibrotactile stimulation with the visual and/or auditory motion. This builds up on how vibrations can be correlated with global motion: for instance most vehicles produce significant non-directional vibrations, which moreover are coupled to their motion. Thus vibrating the seat in accordance with visual or auditory motion allows to enhance the illusory self-motion [9], [15], [24], [25]. Alternatively, walking inevitably produces impacts on the foot sole, therefore a synchronized stimulation of the feet improves the virtual walking experience [21], [43]–[46].

Feet constitute the most common body location in the reviewed papers. Most of them studied the enhancement of virtual walking in seated VR. They were probably inspired by the early findings that showed that even a crude monoharmonic stimulation with minimal visual cues could induce or enhance illusory self-motion [5], [20], [28]. In a visual context suggesting motion but without visual motion cues like an elevator [28] or a train [5], vibrating the foot sole with a crude 50 Hz signal can elicit directional illusory self-motion. Interestingly, in the latter study the perceived direction was clearly determined by the implicit information from the visual scene: sagital in the train scene, vertical in the elevator scene, confused in the bathroom scene. What is more, most participants experiencing a self-motion illusion in the bathroom scene believed, to the surprise of the experimenters, that the room was part of a ship [5]. This outcomes exemplifies how minimal and raw haptic stimulation is able to evoke implicit or even non-existent motion-compatible interpretations.

It is worth noticing that in most of those studies the stimulus is not based on real-world measurements, and often consists in a monoharmonic vibration, which is far from being realistic. The key to ecological validity seems to reside in the temporal synchronization with another modality (visual or auditory), and eventually the dynamic modulation (either in amplitude or pitch). The strength of this technique is the simplicity of using a single vibrator (or a limited number of them), allowing for various implementations on the seat or inside wearables like shoes. Also, the haptic signal does not need great accuracy and can be intuitively drawn from the context. The ButtKicker transducers, which vibrate a home-cinema seat using the low-frequency spectrum of the movie’s audio signal, are a specific but illustrative example of this approach. The main drawback, however, is the heterogeneity of possible haptic stimuli, making it difficult to compare their efficiency. Some authors derived their haptic cues from recordings of an equivalent real scene (footsteps) [21], [44]–[46], or from the ambient sounds of the virtual scene [9]. Others modulated a sinusoidal signal according to virtual motion [24], [25], while some used constant amplitude vibrations [5], [15], [28]. Comparative studies are still needed to assess the best body location (feet or seat), the role of dynamic modulation, or the advantage of measurement-based cues on abstract heuristics.

b) Tactile flow: The other way of representing motion with vibrators is to distribute several vibrators on the body. By stimulating successively a number of contact points, it is possible to display not only a vibrational intensity, but also a direction and a velocity. This method of “tactile flow” has been investigated on the buttock [6] and the finger [22]. However the effect on visually induced illusory self-motion was not significant in those studies. Yet, in a later study Amemiya et al. achieved a significant modulation of perceived forward velocity with tactile apparent motion displayed at the buttock [19]. One advantage of this method is that it relies on explicit parameters (speed, direction, intensity) which allow for psychophysical evaluations. Yet, the design of a proper haptic metaphor remains non-trivial: should the tactile flow speed be equal to the virtual speed? To what extent can it be scaled, in order to match the boundaries of perceptual sensitivity and hardware abilities? Addressing this conceptual issue would help building a parametric rationale in order to undertake comparative studies and develop new technological solutions.

2) Force feedback: Force rendering might seem more suited than vibrations to evoke motion, as it is by definition directional and able to produce actual motion. However, the best choice of a haptic metaphor to provide or enhance motion sensations remains an open question. It is hardly separable from the media content, because force feedback tends to produce displacement, while the workspace is limited. Just like motion platforms, force-feedback haptic motion requires either washout algorithms, or the simulation to respect the workspace boundaries. Yet, aside from technological concerns, the most *perceptually* effective stimulus remains to be identified.

a) Acceleration, Velocity or Displacement?: Should the rendered forces reflect virtual acceleration, or virtual velocity, or else reproduce the body relative movements? This conceptual dilemma was well illustrated by the study of Oishi et al. which attempted to experimentally adjudicate between those three metaphors [7]. The trick was to use a sinusoidal virtual motion so that the three force-feedback stimuli had the same amplitude and only a difference in phase. They asked 12 subjects to adjust the phase in order to match the visual stimulus, and found that for the vast majority of them the setting would match the velocity metaphor. Yet, their second experiment showed that this “velocity” stimulus significantly enhanced the sensation of *Acceleration* and not the sensation of *Velocity*. Also, their setup was based on pulling mechanism which could display only truncated stimuli, weakening the significance of their results.

To our knowledge, only one other study found significantly different results between force-feedback metaphors for enhancing illusory motion, by Ouarti et al. [13]. In their experiment involving 3D navigation in a virtual tunnel holding a force-feedback handle, the acceleration metaphor elicited illusory self-motion significantly more often, and significantly improved subjective assessments of “immersion” and “realism”, with respect to the velocity metaphor and the control condition.

b) Directional polarity: Another debatable choice for designing the force stimulus is its directional polarity: should the applied forces reflect the acceleration/velocity of the virtual vehicle, or reproduce the user’s inertial displacement (being pulled back in a seat when the vehicle speeds up)? In other words, should the direction of the force be the same or opposite to the direction of the virtual acceleration/velocity? Ouarti et al. included those alternatives in their aforementioned study and found similar outcomes, both for the acceleration and the velocity metaphors. They suggested that one half of the subjects preferred one and the other half the other one, which was also mentioned by [17]. Yet other studies did not confirm this assumption or found differences between the two possibilities [8], [16]. More experimental results are needed to draw conclusions on that matter.

c) Torque feedback: An alternate approach with no directionality was proposed by Rietzler et al. [18]. They assumed that for accelerations as short as 0.3 seconds the direction could not be perceived, and they showed that a rotational burst was sufficient to improve significantly the sensations of a visual linear acceleration. This outcome somehow matches the general tenet of the sense of motion, which is ruled by habituation: our motion sensations are most vivid during sudden changes of trajectories rather than a high speed, which remains relative. This perspective goes one more step away from physical simulation, providing cues that might not be self-sufficient to create a strong illusion, but effective in conjunction with visual or auditory motion. In this regard, the transient force feedback approach is similar to the congruent vibrations approach, as both of them seem to rely on a perceptual priming mechanism.

3) Airflow: All authors studying the effect of airflow used an "air resistance" metaphor: the air speed should be ideally proportional and opposed to virtual motion. One exception is Yahata et al. who provided an airflow in the same direction than the simulated motion [40]. The consistency between airflow direction and virtual motion direction was always found, when examined, to be necessary to enhance self-motion sensations [38], [40], [41]. Most studies examined a single and constant speed (both for airflow and virtual motion) [38], [40], [41], [58]. Surprisingly, only one study set the same speed for visual and tactile motion [40]. The relationship between airflow speed and user's virtual speed remains to be studied to determined how different they can be while preserving the positive effect of airflow.

B. Which methods to evaluate haptic motion?

The point of haptic motion being to produce or enhance self-motion sensations, the evaluation of these sensations is crucial to validate this approach. Yet, this is challenging for several reasons. Like any other sensation, it can be measured only indirectly, with the help of specific psychophysical methods. Beyond the usual pitfalls of psychophysical protocols, self-motion sensations in particular are subject to semantic issues. The common language has vague vocabulary about motion, and there is no standard descriptors nor objective indicators for self-motion perception [31]. How to evaluate the impact of a haptic motion system, and with what descriptors to quantify illusory self-motion? From our survey we can draw two distinct conceptual views on self-motion sensations (binary or analog), leading to different scoring methods.

Some authors asked the subjects to push a button or speak out whenever they felt "vection" [5], [20], [22], [24], [28], [40], [41], [55]. This method formalizes vection as a binary cognitive state: we feel it or we do not feel it (with more or less confidence, eventually), independently of the perceived self-motion speed. The strength of this perspective is that it offers clear and relatively reliable metrics for its evaluation: typically average occurrence, onset time and duration. Those authors usually complemented the evaluation with a "compellingness" or "convincingness" rating. One limitation, however, is that it imparts the subject the expectation of a binary perception and tends to discard qualitative sensations.

Yet, the majority of the reviewed studies used a rating (typically as a 0-100 value, sometimes as a 4 to 7 points scale, marginally through a joystick position), expressing a more analog view of self-motion perception. This outlines an intuitive link with the physical quantities of motion, like velocity or acceleration. The wording used for the ratings varied among studies: "Intensity" [9], [15], [24], [25], [55], [56], [60], "Vection strength" or "Sensation strength" or "Strength of the self-motion" [16], [22], [38], [40], [41], [43], [58], "Vection" [18], [44], [46], "Movement" [7], [59], "Self-motion" or "Sensation of self-motion" or "Feeling of self-motion" [13], [21], [45], [57], [61], "Acceleration" [7], [8], [18], "Speed" [7]. Some authors use multiple wordings interchangeably, typically "vection strength" and "vection intensity" or "vection magnitude". In some cases the travelled distance or speed magnitude was estimated [5], [6], [19], [28], in other cases stimuli were compared with a two-alternative forced choice method [13], [20].

Therefore, it is unclear if subjects rated the same sensation, or different aspects of the experience. This impact of wording on experimental results is a significant issue that was investigated, to our knowledge, in only one study so far by Soave et al. [54]. The results suggested that from the subject's perspective, the same virtual motion experience could lead to four distinct and complementary estimations of the associated sensations. For example, it seems that the "perceived self-motion" and the "sensation of movement" are distinct subjective quantities. The possibility that self-motion sensations have several components should be taken an account in further studies and is a valuable lead to evaluation methods and clarify the terminology. Following Soave et al.'s guidelines, future studies might avoid technical words like "vection" and distinguish between four quantities: "sensation of movement", "perceived motion", "user's virtual speed" and "virtual vehicle's speed". This might also help addressing the apparent barrier of the "multimodal saturation problem" (stating that the contribution of haptic cues remains limited when the visual motion cues are already strong, see [60]).

On another note, non-numerical estimates constitute a useful alternative to psychophysical scales (see [63] for an example). Also, the investigation on qualitative descriptors (jumping, running, floating, being pulled, falling, etc...) would be an interesting and exciting research direction to draw near to use cases and applications.

C. The use of multimodal stimulation

In the vast majority of the papers we reviewed, haptic cues were associated with a visual (sometimes auditory) content capable of inducing illusory self-motion by itself: a point cloud [8], [20], [22], a virtual vehicle or a racing game [6], [7], [9], [13], [16]–[19], [61], a 1st person driving video recording [16], [58], a stereoscopic video recording of a walk [21], [44], [46], or walking in VR [40], [45], [59]. Only a few included a haptic-only condition, meaning that the visual-condition is usually considered as the control condition, despite no author used an existing visual stimulus but rather created one. Also, the stimulus was presented either on a screen of through a HMD, with various values of field of view, which is known to affect illusory self-motion [62]. While to our knowledge there was no comparative study so far between the different kinds of self-motion-inducing visual stimuli (point cloud, first person video recording, virtual locomotion), the development of standard visual testbeds would be useful for the community. While point clouds can eventually be described explicitly, there is a lack of detailed metrics to characterize video or VR content.

In 13 experiments out of 33, externals sounds were covered by auditory noise or a sound-cancelling headset. Only a few authors studied "auditory haptic motion" (the enhancement of a vection-inducing auditory stimulus with vibrotactile cues) [15], [25], [55], [60]. The combination of haptic feedback with auditory motion remains to be investigated.

Multimodal stimulation inevitably burdens the experimental protocols by multiplying the possible crossed conditions. Therefore, haptic motion studies might follow two opposite directions. One is to focus on the design of haptic stimulation and its specific efficiency to induce motion sensations in general. The challenge in this case is to ideally have a "neutral" non-haptic stimulus, with well-known effects on self-motion perception. The other direction would be to look for the optimization of cross-modal interactions. In this case the exploration of a large diversity of stimulation both haptic and non-haptic stimuli implies larger scale protocols. As stressed out by Murovec et al., the systematic comparison between modalities within the same setup is largely missing [60].

D. What is the scope of haptic motion?

In this paper, we proposed a set of criteria to help define the field as clearly as possible, yet some borderline cases remain in the "grey zone". For instance, Lécuyer et al. proposed a haptic feedback improving the perception of turns during a virtual displacement [14]. More lately, passive haptics has been suggested as redirecting technique for walking in VR [4]. Also, the techniques inducing an out-of-body experience could be considered. However, we decided not to include them in our selection, as those works did not evaluate self-motion sensations directly.

While the haptic contribution is typically referred as weaker than and complementary to visual stimulation, it is not impossible that a purely haptic input might generate self-motion sensations. This question was never directly addressed to our knowledge, yet the works of Nordahl et al. and Nillson et al. showed that haptic cues could induce illusory self-motion in an ambiguous yet immobile visual context [5], [28]. At this point, it is not clear if one should differentiate between the techniques that *enhance* the illusory self-motion produced by another modality, and the techniques that *induce* or *modify qualitatively* a percept of self-motion.

V. Conclusion

In this paper, we proposed to formalize and survey an emergent research field that we call "haptic motion": inducing or enhancing illusory self-motion by means of localized haptic stimulation. This radical conceptual switch in motion rendering (from objective vehicle motion to subjective sensations) brings up creative innovation directions for motion simulation applications. We believe that the haptic motion paradigm will ultimately lead to innovative technological solutions, more generic multimodal data formalization, new tools for multisensory research, and a richer description of motion sensations that will benefit both to scientific and artistic applications.

We first introduced fundamental concepts of self-motion perception in a virtual environment, and proposed a set of criteria in order to define the scope of this field. Then, we survey 33 experiments out of 31 publications, and classify them according to the modality and body location of their haptic stimulation. We discuss our findings along three research problems, making suggestions for future contributions in the field.

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VI. Biography Section

Anatole Lécuyer is director of research and head of Hybrid team at Inria, Renne, France. Dr. Lécuyer's research interests are in virtual/augmented reality, haptic interaction, 3D user interfaces, and brain-computer interfaces. He is currently Associate Editor of IEEE Transactions on Visualization and Computer Graphics, Frontiers in Virtual Reality and Presence journals. He was Program Chair of IEEE VR 2015-2016 and General Chair of IEEE ISMAR 2017. Anatole Lécuyer obtained the IEEE VGTC Technical Achievement Award in Virtual/Augmented Reality in 2019 and was inducted in the IEEE Virtual Reality Academy in 2022.

Antoine Costes is a researcher and a media artist. He obtained a PhD in Computer Science and Haptics within the HYBRID team of Inria Rennes in 2018, in collaboration with InterDigital, France. His academic research topics include touch and motion perception, haptic interfaces, virtual reality and cross-modal interactions. He also crafts robotics and connected systems for artistic purposes.