Survey of Wearable Haptic Technologies for Navigation Guidance

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***Abstract*—Wearable haptic technologies, known as *wearable haptics*, instantiate physical contacts with users, either to confirm actions or to communicate a surrounding information - over a worn-type interface. Two factors require to be addressed for their design: the body locus - a function of comfort and sensitivity, and the types of stimuli they provide. Wearable haptics have gained great popularity in the last decade, thanks to their effectiveness, ease of use, and variety of application scenarios. This paper provides a non-exhaustive review of the state of the art on wearable haptics for navigation guidance. We classify the existing literature through two dimensions: (1) the body part they stimulate and (2) the haptic stimulation they provide through their actuation technology. We then analyze the navigation guidance strategies they adopt for communicating with the wearer, to finally identify challenges and limitations reflected in their evaluation protocols. Compromises are to be drawn when eliciting guidance through wearable haptics, between acceptability, cognitive workload, usability and accuracy.**

***Index Terms*—Wearable haptics, wearables, navigation guidance, survey, state-of-the-art, guidance strategies, wearable device**

I. INTRODUCTION

HUMAN-ROBOT and human-machine interaction technologies currently aim to provide new ways to interact and exchange information with machines or artificial digital environments. Yet, communicating information between humans and machines requires an effective mediating tool. In these regards, wearable haptic interfaces - haptic systems that users can literally "wear" - are perceived as a viable interaction medium [1], instantiating physical feedback to their users.

Wearable haptics enhance physical interactions, enabling users to feel remote and virtual worlds as well as perform a wide variety of exploration and manipulation tasks. They stimulate the human body (e.g. hands, arm, leg, head) to convey rich touch sensations, in an intuitive and understandable manner, delivered through small, lightweight, and often inexpensive packages [1]. These promising features justify the recent burst of available wearable devices communicating through haptics, which have successfully been employed in a wide range of scenarios, including robotic teleoperation [2], [3], [4], virtual and augmented reality [5], [6], motor rehabilitation and augmentation [7], [8], surgical interventions [9], [10], [11], [12], assistive robotics [13], and navigation.

Wearable haptics have been proven particularly useful and effective in providing navigation guidance information, mostly thanks to their distributed and private rendering capabilities [1]. Haptic cues have been used to communicate turn-by-turn navigation [14], guidance in industrial teleoperation [15], [16], rehabilitation, or assembly tasks [17], and support people with sensory disabilities [18].

This paper provides a non-exhaustive review of the state of the art on wearable haptics for navigation guidance.We analyze the existing literature according to (1) the body part the wearable haptic devices and technologies stimulate, and (2) the type of haptic stimulation they provide. We then describe the navigation guidance strategies they adopt for communicating with the wearer, and finally discuss the challenges and limitations highlighted through wearable haptics for navigation guidance evaluation protocols.

II. DEFINITIONS, BACKGROUND AND SCOPE

In this section, we provide some definitions and background on haptics, wearables, navigation, and describe our scope at these fields' intersection.

A. Definitions and Background

1) Haptics - Perception and Experience: We can consider our sense of touch (or haptic sense) as composed of two sensory sub-modalities, cutaneous and kinesthetic. On the one hand, cutaneous sensations are elicited by receptors and corpuscles embedded in the skin, which are present in different densities and types throughout our bodies. On a perception perspective, they enable us to identify local properties of the environment, such as the shape, temperature, and texture of an object we touch. Cutaneous perception for exploration and manipulation principally relies on measures of the location, intensity, direction, and timing of contact forces on the hands [19], [20], [21]. On the other hand, kinesthetic sensations originate from the muscles, joints, and skin. They enable us to identify the position and velocity of our limbs, as well as the forces they apply [19], [20]. Kinesthesia is indeed strictly intertwined with proprioception. We can define the former as the cognizance of joint movement and the latter as the awareness of our own joints positions [22]. Haptics extends from the design of external stimulation simulating haptic features to the experience it provides on a user perspective. The *Haptic Experience* was defined in these regards [23], discussing design parameters and usability requirements of a haptic stimulation as well as their potential impact on the experiential dimensions influencing the user experience.

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With the growth of haptic technologies, many surveys in haptics are being drawn, from various perspectives. They have focused on haptic interaction techniques [24], haptic rendering technologies [25], [26], [27], or on specific applications such as medical/surgery training [28], [29], [30], virtual or augmented realities [31], [32], [33], telemanipulation [34], industry training [35], or a combination of them [36]. In this survey, we only focus on a class of haptic technology: wearable haptic technologies (see below).

2) Wearable Technologies: Wearables are a group of interfaces that can be worn onto the user's body. This class of devices includes flexible garments (e.g. gloves, t-shirts) and rigid accessories (e.g., watch, glasses, bracelet) [37], [38], [39]. They can be defined as "small electronic and mobile devices, or computers with wireless communications capability that are incorporated into gadgets, accessories, or clothes, which can be worn on the human body, or even invasive versions such as micro-chips or smart tattoos" [40]. They are mainly used for body-tracking, e.g., in sports applications [41], rehabilitation/health monitoring [42], [43] or motion capture, and gained a global popularity as tools for the Internet of Things (IoT) [40]. A wearable therefore provides information about the users and/or its vicinity to an external display. In this survey, we focus on *wearable haptics*: the wearable device itself communicates an information to the users through haptic cues, which includes notifications about the users, their physical environment, or a remote/virtual one. They are defined by Pacchierotti et al. as haptic "interfaces capable of communicating with the human wearers during their interaction with the environment they share" [1].

Wearable haptic technologies have been presented and analyzed according to their field of application (e.g., sensory replacement [44], rehabilitation [45]), the technology they exploit (e.g., exoskeletons [46]), their form factor (e.g., gloves [47]), or the body part they stimulate (e.g., fingertip and hand [1]). In this survey, we provide a classification of wearable haptics technologies according to the body part(s) they stimulate and the applied stimulation. However, we only focus on a single application: navigation guidance.

3) Navigation: Navigation is defined as a "goal-directed travel through space" [48]. It refers to one's ability to displace in a remote, virtual, or physical environment. The literature has often focused on the means to provide users with navigation capabilities in different environments. For instance, users in a virtual environment can be teleported, walk in place, or walk naturally [49]. Using these interaction techniques, users choose their arrival and displace themselves towards it. Nonetheless, in psychology, an entire field of research is devoted to navigation in itself, through spatial cognition, the *knowledge of oneself in relation to our surroundings* [50]. Taxonomies in this area classify navigation as either *locomotion* or *way-finding* [51]. While these terms often refer to the same task outside of the spatial cognition field, they are to be differentiated as they do not rely on the same cognition maps on a user perception perspective. To understand them, three spatial representations are available: (a) landmarks, unique configurations of perceptual events; (b) routes, as a sequence of landmarks; (c) survey or map, as sequences of routes [52].

a) Locomotion: Locomotion refers to "the guidance of oneself through space in response to **local** sensorimotor information in the immediate surrounds" (i.e. obstacle avoidance, moving towards a target) [48]. It therefore only relies on (a) and (b), i.e. the local landmarks in the visible space around self. It does not require an entire mental model or cognitive map of the environment.

b) Way-Finding: Way-finding refers to "the planning and decision making that allows one to reach a destination not in the immediate sensory field" [48] (i.e. choosing the shortest route, orientating to non-local landmarks). Way-finding therefore relies on (a), (b) and (c); and requires memorizing the environment and creating a cognitive map of it. To reduce this cognitive load, way-finding can be aided (using signage, maps, navigation assistant) or directed, when the destination is specific [51].

c) Navigation Guidance: In this survey, the wording "navigation guidance" refers to the spatial cognition's **locomotion**: information provided to the users are in their direct vicinity. Navigation guidance "helps the user to find, locate, and reach a target without having to perform an exhaustive search within the space" [53]. More specifically, techniques providing aided way-finding giving information about the users' surroundings and requiring decision making (presence of stairs, doors, toilets etc. [54]); or unaided directed way-finding for target approximation or path finding (e.g. [55]) are not included in this paper. Similarly, papers on guidance outside of the navigation field (rehabilitation [56], teleoperation/guided manipulation tasks [57]) are also out of the scope of this paper.

This navigation guidance information can be provided through external tools (e.g., GPS) or be directly connected to the user. For instance, visually-impaired people are guided through their white cane, physically discovering their vicinity when moving along an unencumbered pathway. Guidance can also be provided without conveying explicit feedback to the user. Users navigating an environment can be subject to visual illusions and be physically redirected towards a destination without noticing a trajectory alteration [58]. This survey addresses navigation guidance systems providing explicit feedback to the users.

B. Scope

This survey focuses on **wearable haptics for navigation guidance applications**, regardless of the type of information they provide to the wearer (e.g., trajectory tracking, obstacle avoidance). Technologies only providing visual feedback for guidance (such as non-vibrating glasses) are out of the scope of this paper, as to wearable haptics that *could* be employed for navigation but have never suggested to be used in such an application (e.g., a vibrotactile bracelet used for VR contact rendering), or systems whose purpose is to only render some environment properties (e.g., a haptic watch rendering the map of an environment for non-navigational purposes).

The contributions of this work are: (1) a classification of wearable haptics for navigation guidance through two dimensions: body area and stimulation type; (2) an overview of wearable haptics technologies for navigation guidance; (3) an analysis of the strategies to provide guidance information; (4)

a summary of current challenges and limitations highlighted from the devices' evaluation protocols.

III. STIMULATED BODY PARTS

This section analyzes the body parts most often stimulated through wearable haptics for navigation guidance. We describe them according to two dimensions: comfort and sensitivity (see Figure 1) . Comfort relates to the "wearability" of the device (i.e. weight, size, shape, ergonomics) [1], while sensitivity relates to its acuity and related expected performance for communicating guidance during navigation.

Indeed, wearables have the benefit of being directly attached to the body in an often non-invasive, non-obtrusive, and convenient way. Wearable haptics usually rely on rigid controllers or PCBs that therefore need to be worn without compromising the users' comfort and freedom of movement [1]. For instance, a rigid link should not be placed on a body joint, as it would prevent or impair potential limb displacements and rotations. Prior design guidelines for wearable haptics indicate that absolute characteristics (e.g., the weight and size of a device) might be misleading in measuring its "wearability" [1]. Instead, such characteristics should be evaluated considering the part of the body where the interface is worn. As an example, a device too heavy for a fingertip might be perfectly comfortable if worn on the forearm.

In terms of sensitivity, and as per Penfield's homunculus [65], a given artificial haptic stimulation is interpreted differently depending on its location, according to density of mechanoreceptors in the skin [66], [67], [68].

There are many ways to measure and describe sensitivity, according to the target stimulation and information to convey. In general, we define an absolute perceptual threshold as the smallest amount of stimulus energy necessary to produce a sensation, and a differential perceptual threshold, or Just Noticeable Difference (JND), as the smallest amount of stimulus change necessary to achieve some criterion level of performance in a discrimination task [69]. For example, the vibrotactile absolute perceptual threshold (or vibrotactile sensitivity) can be defined as the lowest vibratory frequency/amplitude for which a vibration is perceived. Similarly, kinesthetic sensitivity can be defined as the minimal physical stimulus eliciting a kinesthetic perception, and its acuity defines the accuracy of the estimation of a limb position after having been moved by an external person [70]. Other representative examples for our purposes are the "tactile sensitivity", also referred to as *tactile acuity* or two-point threshold, which has been defined as the distance threshold for which users are able to discriminate a two-point stimulus [71]; the "error of localization" (or "point localization" [71], [72]), which is defined as the separation between a reference point and what is identified by the user as the reference point [73]; and the tactile directional sensitivity (or *shift*), which is defined as the threshold distance for which users are able to tell the direction of a movement [73]. We note that the wording *acuity* in the common vocabulary usually refers to a resolution; though when used in haptics, it often refers to a spatial tactile sensitivity rather than other stimulation (kinesthetic, thermal etc.).

A. Head

The head is a human body part which assembles many receptors in charge of collecting important external information, including vision (eyes), smell (nose), hearing (ears), taste (mouth). It also includes lots of sensitive neurons distributed around the skin of the neck and cheeks. Most of the head parts (neck, ears, forehead, cheeks) also have a high sensitivity to thermal variations, which can be leveraged to provide further information to the user [74].

In this section, we gather systems stimulating the head, including the neck, ears, back of the head, forehead, mouth, and tongue.

Neck. We are already familiar with wearing headbands, necklaces, and earrings; yet, as most wearable haptic devices and technologies require to be in firm contact with the skin, neck devices are usually considered to be too uncomfortable or even dangerous [75]. Sensitivity-wise, the area of stimulation can easily be determined from a single point stimulus [76]. In this respect, the neck was shown to be one of the most effective body part to detect vibratory frequencies (absolute threshold of 0.72 Hz) [77] (see Figure 2.A); however, this refers to the back of the neck, as the front has a lesser tactile spatial acuity [76].

Ears. Most glasses-like haptic interfaces usually stimulate the user at the ears [81], [82], [79] and have the benefit to be able to also easily stimulate the user's vision (see Figure 2.B), which makes it promising for Augmented Reality applications. More generally, ears can be stimulated through earrings-like devices, which seem like a convenient location for wearable haptics [60], providing high sensitivity and comfort. One benefit is their symmetry around the users' head: an independent stimulation of two haptic-enabled earrings can easily indicate the direction to follow.

Back of the head. Many wearables are already available for covering the users' head, often attached to its back. In this regard, we see wearable haptic solutions for guidance with helmets [83], [84], [85], [80] (see Figure 2.C), wigs [86], hats [87], and caps [88], [89], stimulating mostly the back of the head, in spite of its usually lesser sensitivity due to the presence of hair. This can be seen as a compromise, as the back of the head provides the largest head area and therefore can be stimulated to provide spatially more information.

Forehead. The forehead provides a convenient stimulation location as it guarantees an area of application spanning 360° [90]. Moreover, it is rarely employed for other purposes. Headbands such as [91], [92], [93], [62] are therefore quite popular for wearable haptic guidance applications exploiting on the head. Sensitivity-wise, the forehead has a tactile acuity of 15 mm [71] and a 10 mm directional sensitivity (see Figure 1.d). It has been indicated as the best body locus for pressure sensitivity [71], [72] and as the second best area for detecting vibratory frequencies [77].

Mouth. Within the head, the mouth, lips, and tongue are the most sensitive areas to thermal cues [94], yet mostly vibrations cues are currently explored. These areas also are the most sensitive parts of the head according to Penfield's homunculus [65]. They have been exploited by Tang et al. [95] for the delivery of guidance information to blind users.

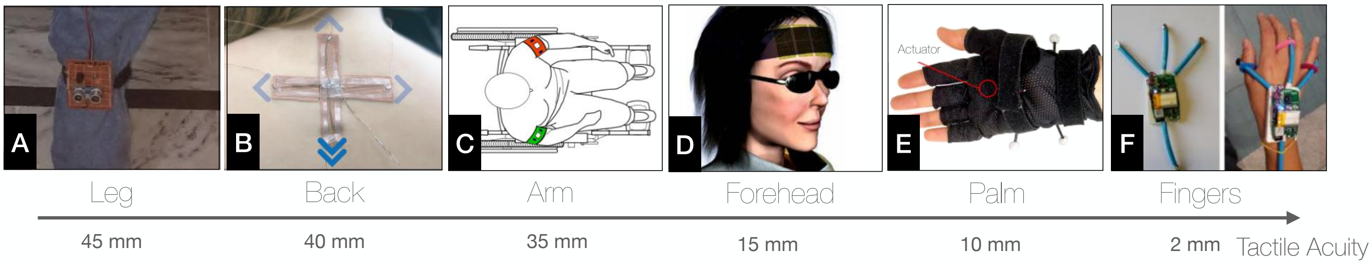

Fig. 1. Body areas for wearable haptics. A trade-off is often made between *comfort* and *sensitivity*. This continuum shows devices for navigation guidance - worn on various body parts according to their respective tactile sensitivity, or *acuity*. (A) Leg-worn device [59]; (B) Back wearable [60], (C) Armbands for wheelchair navigation aid [61]; (D) Forehead headband [62]; (E) Palm device integrated through a glove [63]; (F) Finger rings integrated through a glove [64].

Yet, they are still not popular body areas to stimulate, as they are quite inaccessible and inconvenient: humans swallow their saliva, speak, or eat, and therefore cannot be often encumbered by a tongue device. Moreover, their respective areas are quite limited and do not allow to leverage their high sensitivity (e.g. the upper lip for instance displays a 5 mm tactile acuity [71]).

B. *Torso*

The torso, defined as the central part of the body, including the front and the back sides, is a large and convenient area for wearable feedback, as the stimulation can occur in a garment such as a jacket or a belt [96]. Even though its sensitivity is quite limited compared to other high-sensitive body areas, Piateski and Jones [97] showed that the torso is capable of accommodating twice the information received at the fingertips thanks to its significantly larger area. Sensitivity-wise, the potential presence of fat makes it the worst body locus to detect vibratory frequencies (0.91 Hz) [77]. It features a 30 mm tactile acuity and a 10 mm directional sensitivity for the front, as well as 40 mm tactile acuity (see Figure 1.b) and over 5 mm directional sensitivity for the back [73], [98]. It also displays a 10 mm error of localization [73], similar on the belly and the back - which is almost twice as much as the forehead one. Yet, the torso is the second most sensitive body locus to pressure (after the forehead/face) [72], [71], therefore a large class of pressure-based stimulation exploits this spacious body area.

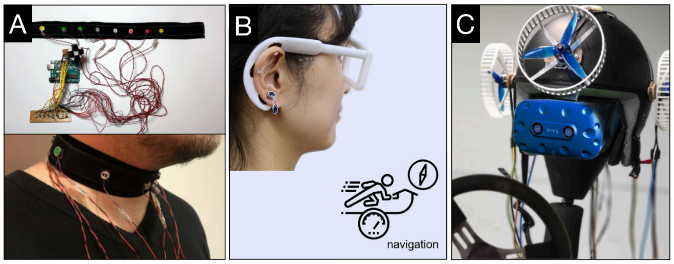

Fig. 2. Examples of wearable haptic systems for the head: (A) Neck collar [78], providing guidance through vibrotactile feedback; (B) Earring [79], associated with AR glasses, communicating guidance information through vibrotactile feedback; (C) Head helmet (back of the head and forehead) [80], providing guidance in VR through kinesthetic feedback.

C. *Arm*

The arm is a very popular and comfortable area for a wearable, that can be integrated in sleeves [99] or arm bands [100], [101], [61]. A large amount of skin is available for stimulation, in various directions (proximal-distal - through its length, e.g. with a sleeve, or lateral-medial - through its circumference, e.g. with an arm band). Arms are also often used for wearing exoskeletons able to provide kinesthetic feedback to the elbow and/or shoulder. In this respect, kinesthetic sensitivity is dependent on both the limb displacement and its velocity. In fact, a movement over the shoulder would have an impact over the entire arm (upper arm, forearm and hand), as a movement on the elbow would directly impact the forearm (and ultimately the wrist would directly impact the hand). For instance, with the hypothesis of a straight 65-cm-long arm, a 1° rotation on the shoulder would cause a 23 mm displacement on a fingertip. The same rotation applied on the wrist joint would only move it by 5 mm, if we consider a hand of 15 cm. Second, regarding speed, the same displacement for a faster movement is detected more easily than a slower one. For instance, at a $10-80^\circ/s$ velocity range, the kinesthetic sensitivity threshold is at 1°; for a $1.25^\circ/s$ velocity it goes up to 8° [102].

In terms of tactile acuity, the global arm sensitivity falls in $35-40$ mm (see Figure 1.c) [71]. A *gap detection* task was also performed on this body area, using a two-*surface* discrimination threshold - as opposed to two-*point* discrimination threshold (what we call tactile acuity here). For this task, the stimulus orientation was shown to have a significant impact on the threshold detection. Indeed, this threshold is above 20 mm for a proximal-distal stimulation (forearm: 23 mm, upper arm: 20.1 mm), and decreases up to approximately 10 mm for a lateral-medial one (forearm: 9.75 mm, upper arm: 12.21 mm) [103]. Frequency-wise, the vibratory threshold is 0.83 Hz [77].

No data was found regarding the upper arm and forearm directional sensitivities. Yet, using the previous information, we can already assume that a wearable can be easily placed on an arm band to provide a lateral-medial stimulation. A kinesthetic stimulation can also be sent to the upper arm for the entire arm to be stimulated, as seen in [104].

Similarly to the ears, the symmetry of the arms (and ultimately of the hands, wrists, legs, and feet) make them great candidate for guidance applications: a direction can be communicated to the appropriate limb whenever required.

D. Hands and Wrist

The wrist, hands, and fingers are the most stimulated body areas when considering wearable haptic interfaces. They regroup bracelets, watches [105], gloves [63] (see Figure 1.e), rings [64] (see Figure 1.f), that however can potentially encumber and impair their use during important grasping and manipulation tasks.

Hands are our main mean of communicating with the environment: we most often explore and manipulate our surroundings using our hands. They are the most represented body areas in Penfield's homunculus: as opposed to the back being represented by the same brain part, each finger has a dedicated brain part, discriminating their respective signals.The wrist has registered a vibratory frequency threshold of 0.83 Hz [77]. As opposed to the arm (see previous subsection), proximal-distal and lateral-medial stimuli are quite similar for gap detection, with ratios (proximal to lateral) around 1 [103]. The palm tactile acuity is around 10 mm and the fingers about $2-3$ mm, which make them the most sensitive areas of the entire body. The fingers also display a 0.1 mm directional sensitivity [73], which is therefore more than 40 times higher than the one on the back and makes it a really promising locus for guidance applications. The high acuity in the fingers is also practical as their small areas would not allow for a stimulation otherwise.

E. Legs and Feet

The lower trunk (legs and feet) is a usually comfortable area for wearables. They can be designed as leggings/leg bands [106], [107], [5], [59] (see Figure 1.a), ankle bracelets [108], [109], [110] or shoes [111], [112], [113], [114]. When a human moves in the environment, these limbs are the most concerned and are therefore less sensitive to external stimuli compared to other body loci, i.e., the movement itself might partially mask the external stimulation provided by a wearable device. We should also consider that the calf, thigh, and gluteal region have a reduced tactile sensitivity ($42-45$ mm [71]) and are less sensitive to vibrations than other body areas [115].

Finally, the ankle and feet seem to have similar sensitivities as the wrist and hands, compared to their attached limb (respectively, legs and arms). The ankle and wrist absolute frequency detection thresholds are also similar (0.83 Hz). The tactile acuity of the feet is around 20 mm. It is the second best area for vibration sensitivity (after the hands) [115]. Similarly, as the fingers in the upper trunk, the toes' tactile acuity is the highest among the lower trunk [116]. Finally, thighs, glutes, and calves are less sensitive to temperature changes than soles and feet.

The advantage of using wearable haptics on this part of the body, despite its lesser sensitivity, is its comfort, its large area, its global symmetry on the body, and the fact that it is rarely used for other activities or devices.

F. Summary

This section analysed the different body parts most often used for wearing haptic devices during navigation guidance, focusing on their comfort and sensitivity. Machida et al. [75] proposed these two dimensions to evaluate which body parts are the most convenient for communicating information through a wearable haptic device. Results showed that, comfort-wise, the ears and wrists (e.g. earrings and watches) are the most appropriate locations to stimulate, while the neck and ankle (e.g. necklace, ankle bracelet) lack comfort from the user's perspective. Sensitivity-wise, signals are easier to perceive on the hands than on the chest or waist. It is also important to consider the function of each body part and how wearing a device can affect them. Indeed, some parts of the human body are usually covered and their skin is not so often exploited for touch (e.g. torso, legs), while others are meant to be left free and commonly employed in exploration and manipulation tasks (e.g. hands). For this reason, choosing the body part most suited for a certain interface and task should consider multiple aspects, going well beyond the mere tactile acuity, also considering its comfort and wearability with respect to its everyday use.

We summarize our quantitative analysis in Table I, as a function of the considered parameters and with respect to each other (+++: best, - - -: worst). This table aims at offering a subjective qualitative overview of the compromises to consider when designing a wearable technology for each part of the body. While we reviewed them considering our target application of navigation guidance, this information is useful for most designs of wearable haptics.

	Comfort	Size	Tactile acuity (2-point stimulus)	Shift	Error of Localization	Vibratory Acuity	Kinesthetic Acuity	Pressure	Thermal
Head	- -	-	+	+	++	-	/	+++	+++
Torso/Back	++	+++	- - -	- - -	- - -	+	/	++	+++
Arm	+	++	+	+	- -	+	+++	+	++
Hands	-	- - -	+++	+++	+++	+++	+	++	+
Wrist	+	- -	++	+	++	++	++	++	+
Legs	- - -	+++	- -	/	- - -	- - -	+++	-	- -
Feet	- -	+	-	/	- -	++	+	- -	- - -

TABLE I

SUBJECTIVE QUALITATIVE OVERVIEW OF RELATIVE CHARACTERISTICS OF TARGET BODY PARTS (+++: BEST, ---: WORST, /: NOT FOUND OR NOT APPLICABLE). INFORMATION IS NOTABLY EXTRACTED FROM [94], [71], [115], [72], [116], [77].

IV. STIMULATION TYPES AND ACTUATION TECHNOLOGY

This section examines the different techniques for generating wearable haptic stimuli during navigation guidance. We categorize what stimuli are generated, how they are exploited to communicate navigation guidance information, and which wearable haptics systems leverage them.

A. Kinesthetic

Exploiting kinesthetic feedback to generate directional cues involve applying external forces and/or torques to a joint or limb (see Section II-A1). Yet, proprioceptive sensations can also be elicited by locally deforming the skin around the joints, as it replicates a joint deformation caused by a limb displacement [121], [122], [123].

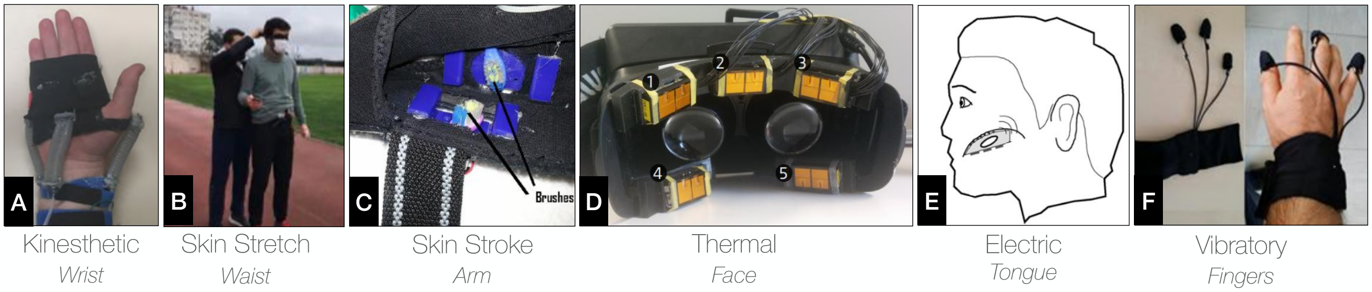

Fig. 3. Our second dimension classifies the stimulation types for wearable haptics. Seven types of haptic stimulation for navigation guidance exist in the literature. We also associate the stimulated body parts in this figure to illustrate their variety from our first dimension. (A) Kinesthetic feedback using *reverse-Pneumatic Artificial Muscles* on the wrist [117]; (B) Skin stretch waist-belt device guiding blinded users [118]; (C) Skin stroke device using brushes to wear on the arm [119]; (D) Thermal feedback provided within a virtual reality Head Mounted Display [120]; (E) Electric signals sent to a mouth-piece worn on the tongue, to guide blind users [95]; (F) Vibrations sent to the fingertips to provide guidance [64].

A kinesthetic stimulation relies on muscles and tendons configurations, and can take advantage of a "reconfiguration" to directly guide the users through their environment. For instance, lower-body *exoskeletons* can literally move the users' limbs to follow the target guidance trajectory [124]. A similar effect can be achieved by directly stimulating the muscles using *Electro Muscle Stimulation* (EMS). It consists of small electrodes attached to the users' skin, which generate an electric signal activating the users muscles to achieve a target motion [125], [126]. In these two techniques, users have thus no say in whether to follow the target direction or not. Their limbs are moved by the system to induce the wanted motion. This physical redirection approach is of course only available when wearing such systems on the lower trunk, e.g., actuating the users legs and feet through an exoskeleton to make them walk towards a target.

Kinesthetic feedback can also provide information to be interpreted. A promising approach consists of a haptic sleeve using *Pneumatic Artificial Muscles* (PAMs), to provide pronation, supination, and abduction guidance feedback [99]. The advantages of PAMs are their safety, light weight, and flexibility. Indeed, they can be easily integrated into a garment suitable for different limbs, generating large forces while providing an easily interpretable guidance information. A PAM, or any other general pneumatic interface attached to a garment (e.g., [127]) can inflate on a side of a limb to indicate the direction to follow, though this inflation is tricky to fully achieve around joints such as the wrist. *Reversed PAMs* (rPAMs) are therefore often preferred on joints. They can be deflated to indicate the direction to follow [117] (see Figure 3.A).

B. Skin Stretch

Skin stretch feedback refers to the deformation of the skin caused by an end-effector moving over its surface. The movement causes no relative displacement within the contact area and hence creates shear and normal stimuli to the skin [1]. Skin stretch offers many possibilities but was also recognized as potentially painful for users [119]. We consider three types of skin stretch for wearable haptics, shear, pressure, and twist, which depend on the direction of the external force generated by the considered device. When the displacement of the stimulation is parallel to the contact surface, it generates shear force; when the displacement is normal to the skin, it generates pressure; when the applied force is twisted with respect to the normal direction of contact [128], [129], it generates a twist.

A common approach to provide skin stretch through shear forces is through *belt haptic devices*. They consist of an elastic belt fitted around a circular limb (e.g., waist [118], see Figure 3.B) and actuated through one or more motors. The actuated belt moves around the limb delivering skin stretch sensations, which direction is exploited to guide users. The intensity of the stretch can be dynamically adjusted by controlling the motor position and speed, so as to map the appropriate target trajectory angle [130]. If two motors are available, the belt can provide skin stretch at different pressure skin levels, which can exploited for guidance in collision avoidance scenarios. In general, skin stretch or skin drag does not require large stretches to provide rich and understandable stimuli, which makes it a very promising approach for small parts of the body, e.g., the fingers [131]. For example, Gleeson et al. [132] placed the users' fingertips on a solid plate and performed guidance through micro displacements of the fingertips skin using a *shear tactor*.

Pressure sensations induced through a skin stretch interface providing, e.g., tapping [133], are currently explored but still rarely used for navigation guidance applications. They can be instantiated through *solenoid actuators*, placed as an array in a wrist band, and generate discrete and binary skin hitting sensations, interpreted as "left" or "right" by the user [134]; or using *shape memory alloys* - SMAs, integrated in flexible ergonomic on-skin stickers [60]. Their contraction provides skin stretch, stretch-induced pressure and motion perception - used for guidance.

Finally, twist sensations are not (yet) represented in wearable haptics for navigation guidance.

C. Skin Stroke

An alternative to the above skin stretch stimulation is providing light skin stroking, which can elicit "tactile apparent motion" effects. Discrete skin stroking signals can indeed be perceived as single smooth continuous signal across the skin [135], "as if a rabbit were hopping on it" [136]. These discrete strokes can therefore communicate a continuous direction to the navigating user. Skin stroking was instantiated in [119] using *brushes* moving (anti-)clockwise, and integrated in a wearable bracelet. The signals are apparently well interpreted for assistance guidance [119] (see Figure 3.C) and wayfinding [137], on top of being comfortable and pleasant to receive.

D. Thermal

Thermal cues are not very popular in the literature for guidance applications. Indeed, they show many drawbacks for providing guidance information to the users. First, only a small range of temperatures ($24°C - 40°C$) is considered as appropriate, safe, and comfortable to send to the users [120] (see Figure 3.D). The thermal resolution of the skin also shows a lower resolution and a longer response time than most visual, audio, or mechanical sensations. Whenever stimulated through temperatures, the skin also requires to be reset back to a neutral state, which therefore induces some potential delays between signals and undermines the detection of new stimuli [138].

Thermal cues are often stimulated through *thermo-electric devices* (most often including Peltier modules), which temperature is a function of the electrical current. They can be integrated into headbands [139], wristbands [140], armbands [138], or earmuff-like devices [74], [141] for guidance purposes. For example, Narumi et al. [141] designed an ear device providing location-dependent thermal information to move in an existing space, which was divided into several thermal fields. People were then guided through the space by distinguishing the different thermal areas. A literal heat-map can also be mapped to the available space, as a gradient of the users' distance to target [138]. A more direct approach consists in designing patterns of thermal modules to provide guidance information using three stimuli variables: location (where the stimulus starts), number (of consecutive spatio-temporal stimuli) and direction ((counter-)clockwise stimuli) [140], [120]. Thermal stimulation is thus subtle to discriminate and its main advantage is its simple integration in wearable haptics, e.g., Peltier elements can be easily embedded in most end-effectors with very little footprint.

While LEDs or other techniques could be used to generate heat in wearable devices, Peltier elements are currently the most popular, as they guarantee a good efficiency with a relatively low voltage, and they ensure no burning sensations when touching the skin.

E. Electric (electrotactile)

In Section IV-A, we already discussed Electro-Muscle Stimulation. Apart from contracting the users' muscles and tendons, electric signals can also be sent through the users' skin so as to directly stimulate the nerve endings and provide tactile sensations. These systems are called *electrotactile interfaces* and provide low-level current pulses to the skin [142]. These interfaces rely on electrodes, which are often flexible and very thin, facilitating their integration in wearable haptics technologies. They can be used as collision avoidance notifiers, for instance to inform users of potential obstacles or landmarks [143], or directly send a direction to follow [144] (see Figure 3.E).

F. Vibratory

Vibrotactile cues are the most often employed to provide guidance information, mostly thanks to their cost-effectiveness and simplicity of implementation.

The human skin is sensitive to vibrotactile stimulation, at different frequencies or amplitudes depending on body loci (see Section III), making vibrations easily noticeable and reliable perception-wise. This justifies why most wearable haptics devices use vibrations, no matter the body area or form factor. However, sustained and prolonged vibrations are known to be uncomfortable [61], [145]. The most popular actuation technologies among them are *Eccentric Mass Motors* (ERM) [146], [147] (see Figure 3.F), where the mass is subject to a rotational force, *Linear Resonant Actuator* (LRA) [148], [92], where the mass is moved up and down along a line with a spring, *voice-coil actuators*, where a permanent magnet is suspended in an electromagnetic coil to produce vibrations [149] and *piezo-electric actuators*, which consist in beams deforming to vibrate against the users' skin [150]. Using the same principle, *electro-active polymers* can also provide vibrations against the user's skin [151]. Indeed, these materials deform as a function of the received voltage; at an adequate frequency, they therefore provide a vibratory feedback [39]. Their flexible materials (e.g., electro-active textiles, dielectric elastomers [39]) seem adapted for wearable applications, though these have not been developed for guidance applications yet.

G. Summary

This section described the different types of feedback for navigation guidance and the technologies enabling them.

Although each of them has its pros and cons vis-à-vis navigation guidance, we can see some interesting and inspiring patterns. For example, compact and easy-to-use solutions such as ERM vibrators are largely the most popular actuation technology for the considered application. This is due to multiple reasons. First, they are inexpensive and trivial to use, which makes them straightforward to employ, even for novice designers. Second, their associated stimuli is familiar (e.g. smartphones notifications), noticeable and understandable. Third, they can be easily integrated into garments, for instance exploiting the symmetry of the human body and providing intuitive guidance cues. However, it is known that sustained vibrations become uncomfortable very quickly. Also, vibrotactile actuators need to be spaced out to be recognizable, preventing their use for navigation guidance in smaller parts of the body. In this respect, skin stretch and skin stroke devices seem very promising, as they need little space to convey rich information, they are not as complicated and cumbersome as, e.g., kinesthetic exoskeletons, and they are faster to react and convey changes in the stimulation than, e.g., thermo-electric devices. However, to provide effective information, skin stretch and stroke devices need to be well fastened to the body, which can make them uncomfortable to wear in some areas, especially for prolonged times. This aspect is also relevant for electrotactile interfaces, where small changes in the position of the electrode with respect to the skin can lead to significant changes in the delivered sensation [152].

This limitation complicates the integration of skin stretch, skin stroke, and electrotactile interfaces in garments or wearable structures. Indeed, the adaptation and customisation of wearable interfaces targeting panels of different users is an open problem in the community [153].

V. NAVIGATION GUIDANCE STRATEGIES

We distinguish two methods for navigation guidance through wearable haptics: either the user is literally physically guided by the interface, or she receives information about her surroundings (e.g. landmarks, routes [48], [52]). In this latter case, stimulation can be either interpreted as a **where** notification (Section V-A), and a **when** direction (Sections V-B-V-C). As mentioned in [53], “guidance systems generally have two characteristics: 1) they orient the user’s body movement, perhaps iteratively, to reach the target location, and 2) they indicate the target location”. This section discusses the different stimulation strategies providing guidance navigation information. As per the Haptic Experience [23], we define the haptic signal *intensity* as the overall perceived strength of feedback and the *density* as its rate or frequency, i.e., the number of noticeable stimuli per a given time.

A. Directions

Guidance information provides directions orienting users, often coupled with some additional strategies described later in Sections V-B and V-C. When providing a direction information, we rely on the *angle to the target trajectory* [130]. To interpret the direction correctly, we can exploit the *causality* feature [23] of the feedback, i.e., the user is required to relate the haptic feedback she receives from its source, identify the direction, and then follow it. Beyond causality, direction is also shown to be better interpreted using *density* than *intensity* [154], [155] (see Fig. 4). In all cases, it is important to ensure that the considered directional sensations are understandable and perceived as different by the user, considering the tactile acuity of each part of the body with respect to the chosen type of stimulation (see Secs. III and IV).

1) Binary direction: 1D Direction: A binary direction can be seen as a 1D direction: it communicates a direction, and provides a *“sense”* (left or right). A straightforward strategy for providing directional guidance is to leverage the symmetry within the body (e.g., one actuator per arm, leg, or hand). For instance, a wearable device on each wrist can be worn to indicate left and right directions, and a simultaneous actuation of both of them indicates a “stop” signal [154]. Similarly, an array of four actuators can be designed, with binary cues to interpret (e.g. left/right, forward/backward [64], [111]), or absolute cardinal directions [137].

2) 2D direction: A 2D direction navigation strategy provides more information than a binary direction one: it is more precise regarding the angles and trajectories to follow. It provides a more accurate *angle information* than a simple sense. A first method is to increase the number of stimulation points: it allows for less interpretation and more intuitiveness, e.g., it can directly communicate the direction to follow in the transverse plane of the human user. The number of actuators and their spatial distance can be used to provide the directional information. For instance, and as a function of the local sensitivity, discrete or continuous signals can be provided [84]. Changing the distance between actuators has been proven to significantly affect the interpreted information: a smaller one conveyed the user with the sensation of a continuous stimulation, exploiting the “apparent motion” illusion - also called “funneling” [156], which was considered better for understanding directions to follow [84]. The sequences of actuation provide different types of directional information: arrays of actuators can be updated regularly to keep the user in the right direction (e.g., every 0.3 s in [144]). Sequences can also indicate all of the wrong directions of an intersection [157]. These “directional interfaces” are defined as “aiding users to orient themselves to find a way-point during navigation tasks” [96].

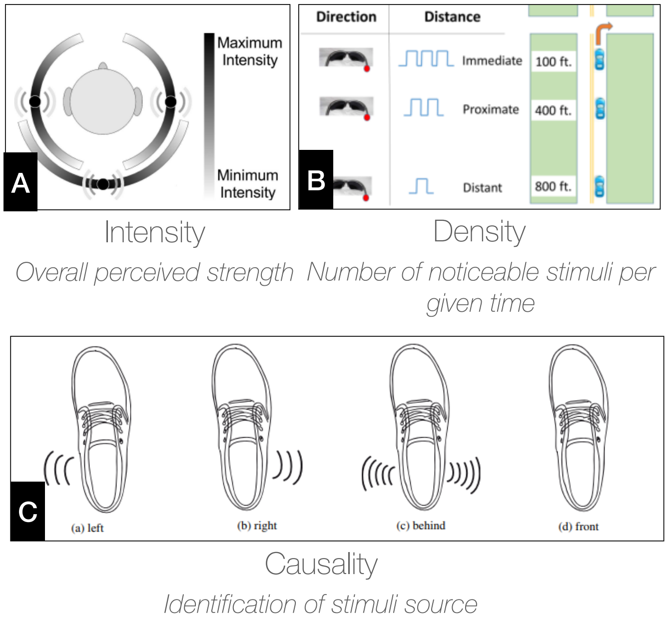

Fig. 4. Examples of haptic feedback parameters from providing strategies to convey navigation guidance, from [23]. (A) Intensity: the stimulation intensity indicates the direction to follow, e.g., [101]. (B) Density: the rate of stimuli per a given time indicates when to take a turn, e.g., [81]. (C) Causality: the user needs to identify the source of the feedback to choose the correct guidance direction, e.g., [111].

3) 3D direction: Finally, there exists techniques to provide 3-dimensional direction information, with a *height or depth* perception on top on a 2D angle. Spatial and dynamic haptic illusion can be obtained by varying the time and spatial sequence of the multi vibrations [91]. As opposed to previous techniques, the directions are updated regularly to guide the user in “real-time”. A good synchronisation between actuators can also provide 3D directions (translation, rotation). For instance, simultaneously stimulating the fingers in opposite directions can indicate hand supination, pronation or flexion, and can be then exploited for navigation guidance [149].

B. Turn-by-Turn (GPS-like)

Guiding a user with a turn-by-turn strategy consists in providing a stimulation *when* she is required to take a turn, similarly to GPS guiding systems. In this case, the navigation information to modulate is the *delay* or *distance before turning*, in addition to the direction to turn to (see Section V-A). The frontier between delay and distance is thin in navigation guidance applications: Kiss et al. [158] provide patterns to "turn far" and "turn near" (*distance information*) to eventually communicate to "turn now" (*delay information*).

Whether they rely on thermal [140] or vibratory cues [159], [160], [161], turn-by-turn information are represented as (a) a change of intensity in the stimulus [159], [101] or (b) a change of density [81], [63]. As an example of intensity change, a thermo-electric wearable device can correlate its temperature to the delay before making a turn [74], [138]. A density change is instantiated with symmetric vibrators in [81], where the frequency varies from 1 to 3 stimuli per 50 ms. With a higher density, the skin can consider the stimuli as continuous, as above the discrimination threshold (see Section III).

C. *Obstacle Avoidance*

Differently from the previous strategy, a wearable haptic system exploiting an obstacle avoidance strategy rely on the *distance to obstacles*. The user is free to choose her trajectory while avoiding obstacles on her way. This approach is similar to using a white cane: it provides haptic feedback whenever a collision might occur [162], [163], [143]. Once again, the feedback can be altered in intensity or density – the closer the obstacle, the stronger or the more frequent the stimulus. This strategy is adapted for vibratory [83], [164], [165], [87] and skin stroke [166] stimuli. In the same regards, a continuous signal can provide a "stop" signal [154], [167], or indicate all the wrong directions to redirect the users and avoid a trajectory deviation [157], [168]. In the same line of observations, this strategy can also be adapted for *target attraction*, therefore relying on the *distance to target*.

VI. CHALLENGES & LIMITATIONS

Providing guidance through haptic signals seems straightforward – a direction, delay, or obstacle is indicated and the user interprets it. Taking advantage of the variety of cues available for stimulation, this information can potentially be very rich. Cues can be intertwined and/or complex patterns can be drawn to provide specific information. Though, wearable haptics for navigation guidance still show limitations - which are usually expressed in the devices' evaluation protocols.

A. *Conceptual User Expectations and Acceptability*

Extensive interviews and surveys have been conducted to define (1) user expectations [169], (2) their prospective acceptability [170], as well as to evaluate (3) wearable devices and technology usability [169], [87] and (4) their requirements [171] for navigation guidance.

Using conceptual prototypes over a 600-participant panel, a survey showed that user expectations for guidance were preferably using visual (over 60%) and cartographic information (over 50%) than haptics (under 10%) [169]. Similarly, acceptability criteria included *utility*, *ease of use*, *ease of learning*, *safety*, *pleasantness* and *self-esteem* and also displayed significantly negative feedback compared to maps [169]. Conceptual vignettes evaluating sensory preferences were also evaluated using the UMUX questionnaire [172] and wearable acceptability questionnaire from [170] (see also Section VI-C). This acceptability is evaluated from an external point of view: the interviewed participants rate their perception of user wearing a head-mounted wearable interface [170]. On a user perspective, they communicate whether the wearable device user seemed independent, needed help or the wearable device, looked cool or nerdy. On an interaction perspective, they rate whether the interaction made them feel uncomfortable, if the wearer seemed awkward, normal, rude, distracting, or if the interaction seemed appropriate. On a device perspective, they evaluate whether the wearable device seemed useful or unnecessary. Users once again preferred navigation guidance through auditory feedback than haptic [87].

Prior to designing a (wearable haptics)-device or technology, identifying user experience dimensions through interviews and experts opinions helps identifying requirements. In these regards, Gustafson et al. [171] defined that wearable haptic devices (1) should be hidden, (2) should not impede on senses working to full capacity, (3) should be easy to use, and (4) should leave the hands free. Another approach consists in identifying the device's principal functions and potential failures, in order to mitigate their risks and/or occurrences and thus optimize the user experience [173].

User expectations are important to consider as they enable the early identification of requirements and provide guidelines regarding the interfaces design. Indeed, even though haptics might not always seem like a promising and/or accepted approach for navigation guidance - we are more used to follow visual and auditory navigation cues than haptics - experimental evaluations highlight a great potential for this type of application (see next subsections).

B. *Cognitive Load*

On a user perspective, the signal provided by the wearable haptic devices and technologies during navigation is required to be intuitive and easy to interpret. This requirement is usually reflected through cognition load quantification, for instance using the NASA TLX questionnaire [174]. This questionnaire evaluates mental, physical and temporal demands, performance, effort and frustration [174]. Haptics for guidance are shown to be cognitively less demanding than vision [82], [84], auditory feedback, or both [87], [81] and guidance through haptics is displayed as intuitive and effective [175].

This cognitive load is also expressed through time for completion, which is shown to be significantly faster with haptics cues compared to visual ones [82], but only to some extent. Indeed, the more signals to interpret, the more cognitive load – which needs to be addressed when giving guidance to a visually-impaired person [176]. A complex pattern providing direction using vibration location and angle using vibration duration such as in [171] might lead to a higher cognitive load and/or a less intuitive understanding. Similarly, actuating two similar wristbands at the same time can be found redundant and produce more cognitive load and less comprehension of the guidance [64].

C. Usability

Another challenge regards the usability of wearable haptic systems for navigation, which is often reflected in the devices' evaluations. The most common protocol for usability is the SUS - *System Usability Scale* questionnaire [177], which was shrunk to four questions in the UMUX - *Usability Metric for User Experience* questionnaire [172].

Visual feedback for navigation guidance shows (non significant) better score using SUS than Haptic & Visual [81]. Similarly, using the SUS scale, auditory feedback was better perceived than haptics for providing directions to blindfolded participants [168]. Haptics was then suggested to assist users to keep straight directions and reduce their deviation while navigating. Similarly as the previous subsection, this usability is actually implementation-dependent. As an example, UMUX scores evaluating potential conceptual feedback modalities in [87] showed that audio feedback using headphones was perceived as the most usable. Yet, in practice, haptic feedback through vibrations and auditory feedback did not show a significant difference using SUS, and were both significantly more usable than visual feedback.

We indeed expect usability to significantly vary depending on the type of task considered, haptic feedback provided, and experience of the user, making the impact of the above results limited to the considered implementations.

D. Resolution & Accuracy

Even though haptics globally seems to reduce cognitive load for navigation guidance applications and is likely to be perceived as usable and viable, a compromise regarding resolution and accuracy error is also drawn [84], [87]. Indeed, when visual and auditory channels are available and free from other stimuli, accuracy seems to be higher than for haptic cues [82], [160], [81]. This might be justified as haptics need to be interpreted, and can often lead to more confusion in orientations, for instance. “Left and right” can be easily recognized (93% recognition rate for [149]), while “up/down” and “forward/backward” directions tend to be harder to interpret (70% recognition rate [149]). Absolute directions are even trickier to communicate and ultimately interpret [96].

Some criticism needs to be added whilst analysing wearable haptics accuracy results for navigation guidance. In fact, some evaluations are conducted with 2-Alternative Forced Choice, which can also increase the devices' results compared to asking the absolute perceived directions. Similarly, complex patterns might be tested with people sitting at the laboratory [82]. We can potentially imagine a drop in the devices performances considering the added cognitive load in an “in-the-field” experience, where participants are to be guided in real-time [178]. Finally, when multiple senses are compared, we have to consider the experiential designs of each condition: haptics might work better for guidance than an augmented reality map containing too many information, but not with a regular map [169]. The participants are also to be accounted for: wearable haptics for seeing, blindfolded or legally blind users might provide different results.

E. Discussion

Future deployment of wearable haptics for navigation guidance purposes will highly depend on the increase of its acceptability and usefulness. As an answer to a locomotion issue or physical disability, wearable haptics are indeed useful - though for global navigation guidance, it still is not perceived as the best modality to stimulate. Signals may seem too complicated to interpret - the same signal can for instance represent a “constraint”, to force the user to follow its opposite direction as if a virtual wall was erected; or on the opposite, can represent the direction to follow. Even so, these directions are lacking referential. Indeed, spatial cognition heavily relies on referential to enable oneself's orientation and knowledge of a future direction to follow. For instance, a wearable haptic bracelet worn on the wrist, vibrating on its left, should indicate to turn left (or as mentioned before, turn right). Though, the wrist has many degrees of freedom, it could induce a change of orientation of the wearable device. In this configuration, will the user have to interpret the signal as an absolute direction or as related to the wrist relative position? We could consider only integrating wearable haptics for navigation guidance in body parts that could act like a compass, for instance on the torso or on the head. However, and as mentioned in our first dimension, comfort and sensitivity are to take into account. Moreover, sensitivity in the field - while navigating - has not been investigated yet: we might not perceive our phone vibrating in our pocket while walking or cycling. In the same line of observations, current resolutions are still low. Real-life navigation does not only require binary directions, but most often many intersections or roundabouts where directions are to be communicated in a precise way. Globally, many compromises are to be drawn in order to design accepted, useful, understandable, usable, accurate wearable haptics for navigation guidance. This enhancement in the deployment of wearable haptics for navigation guidance could be instantiated through the integration of more precepts from spatial cognition - to better answer to users requirement from their perspective.

VII. CONCLUSION

This survey provides an analysis of wearable haptic devices and technologies for navigation guidance according to two main dimensions: (1) their body area and (2) their associated stimulation and actuation technology. We then identify the main navigation guidance strategies using wearable haptic devices. Finally, we describe current challenges and potential limitations of wearable haptics in this context. These limitations are usually reflected through evaluation protocols: haptic cues seem to reduce cognitive load and are usable, but they are still not catering for future users expectations and increase error rates in guidance. We mainly reflect in this paper how compromises need to be drawn when designing wearable haptics technology, notably for navigation guidance. The devices are to optimise the wearability and sensitivity while understanding the requirements for specific users. Depending on the types of users and/or coupling with other multimodal interfaces, they need to communicate clear instructions without obstructing the cognitive workload or usability.

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