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Transcutaneous Electrical Stimulation for Haptics: A Narrative Review

Takashi Ota
Graduate School of Information Science and Technology
The University of Tokyo
Tokyo, Japan
ota@cyber.t.u-tokyo.ac.jp

Kazuma Aoyama
Katayanagi Advanced Research Institute
Tokyo University of Technology
Tokyo, Japan
aoyamakm@stf.teu.ac.jp

***Abstract*—Haptics is one of the critical sensory input modalities through which humans acquire information from both the external environment and their own bodies. Transcutaneous electrical stimulation has been adopted as a sensory presentation technique among the various haptic feedback methods. Due to its high responsiveness and compact and lightweight design advantages, transcutaneous electrical stimulation stands out from other haptic approaches and has been applied in various wearable devices and interfaces. This review examines four types of transcutaneous electrical stimulation methods for haptics, namely electrotactile stimulation, electrical stimulation of nerve bundles, electrical stimulation of muscles, and electrical stimulation of tendons, from the perspectives of applications and device development. By providing a comprehensive overview of these methods, we also identify key challenges in the field and propose directions for future research. Specifically, we discuss five themes: combined electrical stimulation, the need for qualitative evaluation, the risk of confusion from identical terminology in different stimulation methods, the importance of interface research geared toward practical implementation, and individual differences in the perception of induced sensation.**

***Index Terms*—transcutaneous electrical stimulation, haptics, tactile sensation, kinesthetic sensation**

I. INTRODUCTION

Humans acquire information about the external environment and their own bodies through sensory input, which is vital for planning movements. Therefore, sensory input plays a crucial role in research on Virtual Reality (VR) and Human-Computer Interaction (HCI) [1]. Tactile sensation detects direct interactions between the external environment and the skin, while kinesthetic sensation detects the state of one's own body movement. Consequently, haptics is particularly important among sensory inputs for recognizing phenomena that occur in close proximity to the human body [2]. Transcutaneous electrical nerve stimulation (TENS) is one of the haptic presentation methods that applies an electric current from electrodes placed on the skin surface. Because TENS can present various sensations, including tactile, kinesthetic, taste, smell, and vestibular sensations, it has been utilized in various fields ranging from VR and HCI to rehabilitation medicine [3].

Although there are numerous haptic presentation methods, such as vibration stimulation, mechanical deformation stimulation, pneumatic stimulation, ultrasonic stimulation, and thermal stimulation, TENS is distinguished from the other haptic methods by combining high responsiveness, lightweight/small device design, and low power consumption [4], [5]. Therefore, TENS is integrated into various wearable devices. However, to the best of our knowledge, no review articles discuss research on TENS across haptic research spanning tactile and kinesthetic modalities, although various wearable devices and interfaces have been proposed for different use cases (e.g., tactile presentation, kinesthetic presentation). As a result, novice learners require considerable time to grasp an overview of previous research on TENS for haptics. Therefore, this review article aims to widely organize research on TENS for haptics by classifying it according to certain criteria. Moreover, we discuss issues highlighted by the classification and offer guidelines for future research on TENS for haptics.

II. METHODOLOGY

A. Format of this review

This review is written in the form of a narrative review. Research on TENS is conducted not only in the fields of VR and HCI but also in the field of rehabilitation medicine. Depending on the field, research on TENS varies in experimental protocols and evaluation criteria. Therefore, we deemed it inappropriate to compare the studies from different research fields systematically and instead adopted a narrative review format.

B. Literature collection method

We collected relevant literature using major academic databases, Google Scholar[1], IEEE Xplore[2], and ACM Digital Library[3]. In our searches, we used queries that combined keywords such as "Transcutaneous electrical stimulation," "Haptics," "Tactile sensation," "Kinesthetic sensation," "Electrotactile stimulation," "Electrical nerve bundles stimulation," "Electrical muscle stimulation," "Tendon electrical stimulation" with appropriate logical operators. We also examined the references cited in papers obtained through these searches as needed. The search range was limited to papers published up to January 2025, and only those written in English were included.

[1]https://scholar.google.co.jp/
[2]https://ieeexplore.ieee.org/
[3]https://dl.acm.org/

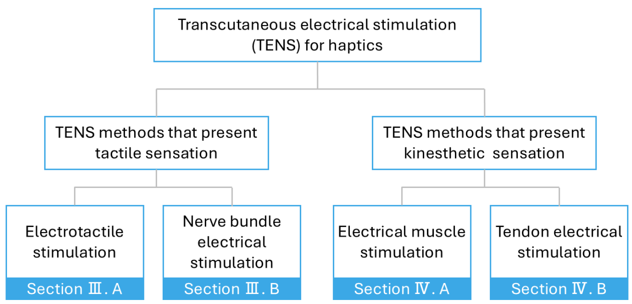

Fig. 1. Classification of TENS methods in this review.

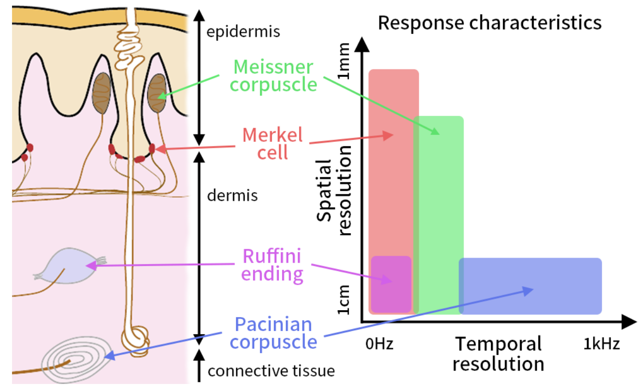

Fig. 2. Four types of receptors in the skin (left), and their spatial and temporal response characteristics (right). This figure was created referring to [12].

C. Scope and organization of this review

This review focuses on research on TENS for haptics. The term "haptics" has various definitions. In this paper, we follow the position that defines haptics as manual interactions with environments, such as exploration for extraction of information about the environment or manipulation for modifying the environment. In that position, haptics is divided into two main categories: (1) tactile sensation (the sensation from the skin in contact with objects) and (2) kinesthetic sensation (equivalently, proprioception) [6].

Accordingly, in this review, we classify TENS methods for haptics into two types: those for presenting tactile sensation and those for presenting kinesthetic sensation (cf. Fig. 1). Further, we divide TENS for presenting tactile sensation into electrotactile stimulation, which activates receptors to induce tactile sensation, and nerve bundle electrical stimulation, which activates afferent nerves to induce tactile sensation. We introduce relevant studies on TENS for presenting tactile sensation in Section III. Next, we divide TENS for presenting kinesthetic sensation into electrical muscle stimulation, which induces muscle movement, and tendon electrical stimulation, which presents force sensation without causing direct movement. We introduce relevant studies on TENS for presenting kinesthetic sensation in Section IV. Finally, we comprehensively discuss TENS for haptics and present guidelines for future research in Section V.

D. Positioning of this review

In the field of haptics, several review articles on TENS have already been published. However, some focus solely on electrotactile stimulation [5], [7], some focus only on TENS of the upper limb [8], and others primarily compare TENS with other tactile presentation methods [9]–[11]. As mentioned, TENS for haptics consists of TENS for presenting tactile and kinesthetic sensations. To the best of our knowledge, while one review article on electrotactile stimulation includes sections discussing electrical muscle stimulation [8], no review articles comprehensively cover all aspects of TENS for presenting tactile and kinesthetic sensations. Therefore, this article discusses TENS methods for presenting tactile and kinesthetic sensations. This paper aims to provide novice learners with an overview and research guidelines of TENS for haptics. In other words, this article provides a framework for appropriately classifying existing research on TENS for haptics. Furthermore, it extracts the findings by overviewing existing research based on the classification.

III. Transcutaneous Electrical Stimulation for Tactile Sensation

There are two categories of TENS for presenting tactile sensation: electrotactile stimulation and nerve bundle electrical stimulation. Because both techniques induce tactile sensations, they are often collectively referred to as electrotactile stimulation [5]. However, since their underlying mechanisms and applications differ, it is rational to treat them separately. Accordingly, this section reviews prior research on electrotactile stimulation and nerve bundle electrical stimulation from the perspectives of their mechanisms and properties, applications, and stimulation devices.

A. Electrotactile stimulation

Electrotactile stimulation induces tactile sensation by applying electrical current through the skin's surface to activate tactile receptors located beneath the skin. In human skin, there exist Meissner corpuscles, Merkel cells, Pacinian corpuscles, and Ruffini endings [13]. Each of these receptors responds to different types of stimuli (low-frequency vibration, pressure, high-frequency vibration, and skin deformation, respectively) [14]. They also differ in spatial and temporal resolution, are located at different depths, and have different axonal orientations (cf. Fig. 2). Based on these facts, various approaches have been proposed to independently stimulate each type of receptor [15], [16]. Specifically, for efficient stimulation of Meissner's corpuscles, anodal stimulation is used; for Merkel cells, cathodal stimulation with a short distance between the cathode and anode is used; and for Pacinian corpuscles, cathodal stimulation with a longer distance between the cathode and anode is used. By selectively applying these different stimulation modes, it has been confirmed that qualitatively distinct tactile sensations such as roughness, friction, fine texture, and hardness can be presented [12], [17].

Building on these fundamental findings, electrotactile stimulation was confirmed to present various sensations. Weak currents can present itching sensations [18], and suitably designed stimulation patterns can represent surface features such as bumps and grooves [19]. Furthermore, by stimulating Merkel cells with specific patterns, the user can perceive a directional force vector. This is because electrical stimulation simulates the gradient distribution of the skin deformation caused by force sensation, resulting in users perceiving directional force sensation [20]. Similarly, force sensation can be presented by cathodic stimulation at the lateral side of the finger, which primarily targets Merkel cells [21].

Electrotactile stimulation offers high responsiveness, compactness and lightweight design advantages compared to mechanical stimulation, and there is no need to consider resonant frequencies, [22]. Various studies have explored ways to combine electrotactile stimulation with other forms of stimulation. For example, combining electrotactile stimulation with vibration has been investigated [12], [23], [24]. Integrating DC motor-based high-frequency vibration with electrotactile stimulation can stimulate Pacinian corpuscles, which are somewhat challenging to stimulate solely with electrotactile stimulation [12], [24]. Studies have also examined the interplay of electrotactile stimulation with other stimulation methods. For instance, research has shown that combining mechanical stimulation can shift the perception threshold for electrical stimulation [25] and that mechanical stimulation can mask the distinctive and sometimes unnatural sensations produced by electrical stimulation [26].

A notable characteristic of electrotactile stimulation is precise spatial control of tactile presentation by placing electrodes directly above the receptors. Electrotactile stimulation can present highly detailed tactile information using dense arrays of multiple electrodes. Consequently, electrotactile stimulation is a promising technology for information presentation devices such as braille displays. Also, with its inherent advantages of being small in size, light in weight, highly responsive, and consuming low power, which are common characteristics of TENS in general, applications to compact and wearable devices are highly anticipated. Since this review aims to classify and extract broader insights for TENS methods for haptics, we focus here on notable research from the perspectives of applications and devices. Because a significant body of research on electrotactile stimulation has emerged since the concept was first proposed in 1973 [27], there are already several excellent review papers focusing on electrotactile stimulation [5], [7]. Readers seeking more detailed information specific to electrotactile stimulation are encouraged to refer to these works.

1) Applications: In this section, we introduce application-oriented studies on electrotactile stimulation that present specific use-case scenarios. A large volume of work has explored applications of electrotactile stimulation. Since the 1990s, it has been studied to present tactile information to visually impaired computer users [28]. Such a display, which presents tactile sensations by applying an electric current through an anode and a cathode on the surface of the skin, is called electrotactile display. By arranging multiple electrodes in a matrix, various tactile patterns can be rendered [29], thereby increasing the amount of information that can be presented to the user. Electrode components of electrotactile displays can be fabricated thin and transparent, enabling them to be overlaid on mobile devices [30]. Additionally, cylindrical grip-type tactile devices with multiple electrodes arranged around the palm have been proposed to deliver tactile sensations across the entire palmar region [31]. To prevent restricting the user's hands from freely interacting with the environment, ultrathin, soft, on-skin electrotactile displays have been proposed for the palm [32], [33]. On-skin or glove-type tactile displays are proposed for interactive VR applications. For example, electrotactile display for enhancing contact information for mid-air interactions with virtual objects [34] and haptic display that combines electrotactile stimulation with vibration and thermal stimulation in a glove for delivering tactile sensation in VR [35]. Another research integrated electrical stimulation via finger-mounted electrodes with force feedback devices to enable the presentation of finer shapes to users [36]. These devices do not require the user to hold them constantly, allowing the hands to maintain free postures. Electrotactile displays have also been used as Braille displays for visually impaired users. For example, a device has been developed that employs OCR to recognize printed text in real-time and convert it to Braille via an electrotactile display [37]. One experiment on sighted participants reported that certain subjects could recognize Braille presented through electrotactile displays with over 90% accuracy [38].

Electrotactile stimulation has also been found effective on body parts beyond the upper limbs. For example, an insole with multiple electrodes embedded inside a shoe has been proposed to deliver tactile sensations to the plantar region [39]. Other proposals include electrotactile stimulation devices targeting the lips [40] and the tongue [41], [42]. They are intended to provide tactile feedback when the hands are occupied by other tasks. Additionally, electrotactile stimulation of the tongue has been explored for rehabilitating patients with functional speech disorders [43]. Electrical stimulation of the torso is also studied [44].

2) Stimulation devices: Multiple high-density electrodes are commonly used for electrotactile stimulation. One reason is that two-point discrimination thresholds (TPDT) for electrotactile stimulation at the fingertip are below approximately 7.0 mm [45] – 7.25 mm [46], indicating that users can discriminate closely spaced electrode arrays. Electrodes are typically made of stainless steel, carbon, or gold-coated materials [4]. To selectively stimulate nerves directly beneath an electrode without interference from adjacent electrodes, such dry electrodes are commonly used in electrotactile stimulation. Sometimes, they can be used in conjunction with a conductive gel layer. The circuitry of TENS devices often employs either voltage control [47] or current control [29], with the latter being more common because it delivers a constant current regardless of the skin's impedance. Multi-electrode electrotactile stimulation typically uses cathodic stimulation to efficiently activate Merkel cells for pressure sensation [48]. In cathodic stimulation, the electrode directly above the target point serves as the cathode, while multiple surrounding electrodes act as anodes. A key challenge with electrotactile displays is the instability of perception when contact conditions between the display and the skin change. Various control techniques have been proposed to address this, such as applying low-level pulses prior to the main pulse [49] and dynamically modulating the pulse width [50]. For additional information on detailed device designs for electrotactile displays, refer to [4].

B. Nerve bundle electrical stimulation

Nerve bundle electrical stimulation elicits tactile sensation by applying current between electrodes placed on the skin surface to stimulate nerves within the body. This technique targets the afferent nerve bundles connected to the desired region for tactile presentation [51], [52], whereas electrotactile stimulation primarily targets afferent neurons connected to the tactile receptors in the skin. For example, sensory afferent fibers innervating the hand transmit tactile and other somatic sensory information to the central nervous system via the median, ulnar, and radial nerves [13]. Leveraging this, researchers have shown that stimulating the wrist [51], upper arm [53]–[55], or area near the clavicle [52] can induce tactile sensations in the hand. Similarly, in the lower limbs, the principal nerve bundles (the peroneal, tibial, and sural nerves) can be stimulated by placing electrodes around the knee [56] or ankle [57], to present tactile sensations to the sole or dorsum of the foot. It is also possible to stimulate the central part of a finger to induce tactile sensations in the fingertip pad, enabling the presentation of various surface textures [58].

A key advantage of nerve bundle electrical stimulation is that it can present tactile sensations at a site distant from the electrodes themselves. Most tactile displays aim to present tactile sensations in the hands or feet, which are important end effectors for interacting with the environment. If the device covers these body parts, it can hinder real-world interaction. In contrast to electrotactile stimulation, nerve bundle electrical stimulation can produce tactile sensations without physically covering the target region.

However, because nerve bundle electrical stimulation directly stimulates nerve bundles, it is more challenging to precisely control the spatial location of the perceived tactile sensation than electrotactile stimulation. Specifically, studies involving wrist [51] or ankle [57] stimulation show that, although the area of perceived sensation varies with the stimulation site, the sensation typically follows the corresponding nerve tract. Consequently, it is generally reported that nerve bundle electrical stimulation offers less precise control over the specific area of tactile presentation than electrotactile stimulation [57].

Nerve bundle electrical stimulation also induces tactile sensations. Therefore, it is sometimes called electrotactile stimulation [59]. However, this review distinguishes it due to its focus on stimulating nerve bundles to generate distal tactile perception, which differs from the direct receptor stimulation approach.

1) Applications: Two promising application domains exist for nerve bundle electrical stimulation. The first is superimposed tactile presentation. This technique enables the delivery of artificial tactile sensations without obstructing the target body part, allowing real-world tactile experiences to be seamlessly combined with electrical stimulation. For instance, a wrist-worn interface designed for augmented reality (AR) applications has been proposed to provide context-dependent tactile sensations to the hand [60]. This compact, lightweight, and wireless device is worn on the wrist, enabling free interaction with the real-world environment and delivering appropriate tactile cues in AR. Another example is a system that places electrodes on the dorsal side of the hand to stimulate fingertip nerves, providing AR-based tactile feedback [61]. Such nerve bundle electrical stimulation, where the tactile presentation area and electrode placement are relatively close, can stimulate the more distal portions of the nerve bundle. This allows for relatively fine-grained control over the tactile presentation area compared to other nerve bundle electrical stimulation methods. Applications of this type of nerve bundle electrical stimulation also include a discreet, efficient tactile feedback system for dental technicians using a wax rod and knife [59].

The second application domain is tactile feedback for upper-limb amputees. By stimulating afferent nerves, nerve bundle electrical stimulation can present hand-region tactile sensations even for upper-limb amputees who have lost their hands (and thus their cutaneous hand receptors) [62]. Some upper-limb amputees experience phantom limb pain, a condition in which they perceive pain in their missing limb. Nerve bundle electrical stimulation has also been investigated as a treatment for phantom limb pain [63]–[65]. Moreover, users of prosthetic hands often rely heavily on visual feedback in daily life, resulting in a high cognitive load. Consequently, nerve bundle electrical stimulation has been explored as a method to provide tactile feedback for prosthetic hand users [66]–[70]. Experiments recruiting amputees reported that nerve bundle electrical stimulation presented multiple distinct types of tactile sensations to the phantom hand [68]. Additionally, this technique can provide continuous tactile sensations of objects in contact with a prosthetic hand, referred to as apparent moving sensations of tactile (a perception of movement along a specific region on the body) [69]. Nerve bundle electrical stimulation is also applied for sensory feedback to lower-limb prosthesis users [71].

2) Stimulation devices: Most studies use commercially available disposable electrodes, such as adhesive electrodes for muscle stimulation [65] or electromyography electrodes [57], based on images from the literature. Compared to electrotactile stimulation, nerve bundle electrical stimulation targets deeper nerve bundles, thus requiring higher current. As a result, relatively larger electrodes are used in nerve bundle electrical stimulation to keep the current density below a certain level.

Therefore, such gel electrodes are often used for this purpose. Both voltage-controlled [67] and current-controlled [67] circuits have been reported effective, but current-controlled circuits are more common, similar to electrotactile displays, to maintain stable stimulation despite variations in sweating and other factors. Some fundamental research, such as the study of stimulation parameters, uses commercially available current-controlled biological stimulation devices (e.g., Tucker-Davis Technologies RZ5/IZ2H-16, Warner Instruments STG4008) [52], [72]. Multi-electrode systems are also sold commercially (e.g., the tecnalia Maxsens), used in some studies to deliver tactile feedback to prosthetic hand users [73]–[75]. Since nerve bundle stimulation targets deeper nerves rather than the superficial cutaneous receptors, the distance between the anode and cathode is typically greater than in electrotactile stimulation [51], [57]. For the current waveform, a direct current (DC) wave [51], [57] or periodic waveform [52], [72] are employed. One study reported that alternating current (AC) waveforms are more likely than direct current (DC) waveforms to induce tactile sensations near the electrode [51]. This phenomenon is thought to occur because Meissner corpuscles, which are sensitive to light touch, are more readily stimulated near the anode.

IV. Transcutaneous Electrical Stimulation for Kinesthetic Sensation

There are two categories of TENS for presenting kinesthetic sensation (i.e., information about body movement, position, muscle, and joint states): electrical muscle stimulation (EMS) and tendon electrical stimulation. Both methods present kinesthetic sensation, but there is a fundamental difference between them: EMS actually causes muscle contraction, whereas tendon electrical stimulation only presents a force sensation. Because of this distinction, their applications differ substantially. Therefore, this section organizes prior research on EMS and tendon electrical stimulation in terms of mechanisms and properties, applications, and stimulation devices.

A. Electrical muscle stimulation

Electrical muscle stimulation (EMS) applies electrical current through surface electrodes to depolarize alpha-motor-nerve fibers, thereby eliciting muscle contractions [76]. In denervated muscle, higher-intensity EMS can also directly excite muscle fibers. In the context of rehabilitation medicine for muscle strengthening, the technology is often called neuromuscular electrical stimulation (NMES), whereas in contexts supporting motor function in patients with nerve injuries, it is called functional electrical stimulation (FES). When electric current is applied, the membrane potential of the muscles or motor nerve fibers changes, generating action potentials that lead to muscle contraction. EMS can induce muscle contractions in various parts of the body, including the upper limbs [77], [78], lower limbs [79], and areas around the head [80], [81].

A defining feature of EMS is that it causes actual muscle movement. In other words, it can induce movements that the user did not voluntarily initiate. EMS affects not only sensation but also body posture. Because EMS can forcibly move the body, it holds promise for supporting sports activities and daily life movements, and various studies have explored movement-inducing interfaces. Conversely, when EMS induces muscle contraction, a corresponding sense of force arises if the user tries to resist that contraction [77], [82]. Thus, some research uses EMS primarily to physically change posture (movement-inducing interfaces), while other research leverages the sensation evoked by EMS or the reflexive sensation against EMS mainly for force feedback (force-presentation interfaces). These objectives often overlap, so a strict division is challenging. Nonetheless, whether the main goal is movement induction or sensation presentation remains an important perspective in reviewing EMS-based interfaces. Section IV-A1 introduces EMS applications for movement-inducing and force-presentation interfaces separately.

1) Applications: As a movement-inducing interface, "PossessedHand" was proposed to drive finger movements by stimulating the muscles of the forearm [83], [84]. By varying the stimulation site, this device can elicit a range of finger postures. Later, the same research group developed "UnlimitedHand," which adds photoreflector-based muscle sensing to the PossessedHand system [85], thereby greatly reducing the time required for calibration compared to previous approaches. Additionally, to address the challenge of independently driving the index, middle, and ring fingers using EMS, an interface that places electrodes on the back of the hand was proposed, enabling more precise individual finger movement [86]. Furthermore, to solve the issue that EMS alone cannot maintain a finger at an exact angle, a device was introduced that augments EMS-induced muscle movement with a mechanical brake [87]. Recently, it has also been found that finger movement can also be induced by placing electrodes on the wrist. This led to the development of a wearable device that integrates EMS into a smartwatch, a wearable device already widespread in society [88]. This system includes a compact stimulator, battery, wireless controller, and 12 electrodes embedded around the strap. By sending cross-sectional currents through these wrist-level electrodes, the band can reliably flex or extend individual fingers and the wrist, giving force-feedback without the bulky forearm pads typical of conventional EMS setups. Incorporating EMS into an existing, familiar wearable device could reduce setup complexity and enhance usability. These systems, which can move fingers without covering the hand, are envisioned to support finger-based tasks such as text entry, musical instrument performance, and crafts [83], [87]. Examples of using EMS for movement support include a system that guides a user's arm while drawing [89], a system for improving bowling skills [90], and a system that reduces cognitive load by automating subconscious tasks (like stirring soup) so users can focus on more cognitively demanding tasks (such as writing an essay) [91]. Furthermore, EMS has recently been leveraged to facilitate the acquisition of "synergistic" upper-limb movements in musical performance. By stimulating the deltoid muscle during practice, the system made the "thumb-under" technique easier and produced more even keystrokes [92].

Several studies applied EMS to movement-inducing in other body parts as well. For example, one system steers the user's walking route by applying electric current to the sartorius muscle in both legs [79]. The same principle of EMS-based path alteration has also been applied to VR locomotion [93]. This work proposed redirected walking using EMS-induced changes in walking trajectory, enabling wide-area virtual exploration within confined physical spaces without compromising the natural walking sensation. Another system employs electrical muscle stimulation to correct running posture, with a specific focus on the foot angle at ground contact. Stimulation of the calf muscles modulates a foot strike posture, reducing the risk of injury [94]. There is also a system proposed for rotating the head via EMS to the neck muscles, intended as a method of gaze guidance in AR applications [80].

Several studies have focused on EMS for human motor control. When humans perform movements in response to visual signals, inherent processing delays occur along the neural pathways that transmit these signals to the brain and subsequently relay motor commands to the muscles [95]. However, because EMS forces muscle contraction, it can trigger movements more quickly than normal human neural transmission allows. Studies have investigated whether users retain a sense of agency over these movements, even when they are induced at speeds beyond normal human capability [96], [97]. This finding might be helpful for integrating EMS into motor support for intensive sports.

On the other hand, many studies have focused on EMS as a force-presentation interface. When users resist the muscle contractions elicited by EMS, they experience a sense of force [77], [82]. Leveraging this effect, researchers have proposed various EMS interfaces, including a mobile force feedback device [77], an arm interface that simulates impact sensations [98], and a system for simulating collisions with a virtual wall [78]. Another interface overlays haptic feedback on the arm when interacting with on-screen virtual bumps [99]. Numerous studies have also applied EMS-based force feedback to VR and mixed reality (MR) applications. For instance, one study reported that providing EMS-based force feedback against a virtual wall enhanced the sense of presence in VR [100]. Another found that EMS-based force feedback enhanced the sense of presence during VR cutscenes featuring collisions with cars, handshakes with a female avatar, and user attention to a key held in the user's hand [101]. Force feedback using EMS is also being applied to VR psychology. Researchers have proposed using EMS to alter the perceived weight of lifted objects in VR [102]. In MR applications, EMS-based force feedback can modulate sensations of touching objects during interactions with physical objects [103]. Some devices integrate sensors into EMS interfaces, such as a device that tracks wrist angle and provides force feedback via EMS [104], and devices that combine EMS with electromyography to enable two-way interaction [105], [106], proposed for applications like rehabilitation. In robotics, EMS-based force presentation has been employed for bilateral robotic control, transmitting external forces on the robot to the user via haptic feedback. By applying EMS to muscles such as the biceps brachii, triceps brachii, deltoid, pectoralis major, and trapezius muscles, advanced force feedback can be achieved, enhancing operational performance in bilateral robot control [107].

TABLE I
MECHANORECEPTORS SURROUNDING SKELETAL MUSCLES.

Mechanoreceptor	Spindles	Tendon organs (Golgi tendon organs)
Connected neuronal fibers	Ia fibers	Ib fibers
Detected information	Muscle length	Muscle tension
Roles	Respond rapidly to muscle stretching	Protect muscles from excessive contraction
Reflex	Ia reflex (contract a muscle)	Ib reflex (Relax a muscle)

Researchers have also explored EMS-based force feedback for other body parts. Examples include an interface that stimulates large areas from the thigh to the lower leg [108], a VR application that simulates natural walking sensations via EMS to the lower limbs [109]. Studies targeting the head include an EMS-based interface applied to the masseter muscle, which presents virtual eating sensations by inducing force sensation in the jaw [81].

2) Stimulation devices: Because EMS must deliver sufficient current to the muscle (or motor nerve) to induce muscle contraction, the anode and cathode are often placed relatively far apart. Therefore, the stimulation hardware is similar to that used in nerve bundle electrical stimulation. Various stimulation devices are commercially available for medical or research purposes (e.g., RehaMove, HASOMED GmbH, Germany) and are used in studies on EMS. Moreover, an open-source EMS toolkit is available for research [110]. For multi-channel EMS devices that switch stimulation among multiple muscles, H-bridge circuits are commonly used [111].

Efficiently inducing muscle contraction with EMS requires targeting the motor point (MP) [112]. However, there is a considerable inter-individual variation in MP location [113], making it difficult to precisely place electrodes on the correct spot. Various methods have been proposed to address this issue, such as estimating MP location by tracking the elbow angle [114] or using mechanomyography to find and stimulate the MP via an electrode array [115].

B. Tendon electrical stimulation

Tendon electrical stimulation is another TENS method for force presentation. Two key somatosensory receptors are associated with skeletal muscles: muscle spindles located within the muscle, and Golgi tendon organs found in the tendons. These two types of mechanoreceptors have distinct properties [116] (Table I).

Although this section focuses on tendon electrical stimulation, it is useful to contrast it with electrical stimulation of spindles (or Ia afferent fibers), not within the tendon itself. Some studies have reported that stimulating Ia fibers can induce reflexes that lead to muscle contraction during nerve bundle electrical stimulation or EMS [117], [118]. However, because these reflexes are essentially byproducts of nerve bundle or muscle stimulation, selectively activating only muscle spindles or Ia fibers with surface electrodes is considered challenging [119]. In other words, this technique also produces other tactile sensations or invokes muscle contraction. Thus, while Hoffmann reflex (H-reflex) testing is used clinically to assess nerve damage [120], it is rare to use muscle spindle or Ia fiber stimulation as the primary target in electrical stimulation interfaces.

On the other hand, the method of conveying force sensation by stimulating Golgi tendon organs is known as tendon electrical stimulation, and this approach holds promise for sensory presentation interfaces. Previous work has shown inhibitory effects on muscle contraction when electrically stimulating the gastrocnemius tendon [121], as well as illusions of arm movement induced by stimulation around the dorsal wrist tendons [119] or the flexor tendon near the elbow [122]. Two hypotheses have been proposed regarding the mechanism for the force sensation arising from TENS: one attributing it to stimulation of cutaneous receptors and another to stimulation of Golgi tendon organs. Experimental findings indicate that a stronger force sensation occurs when the current penetrates deeper into the body (i.e., when the anode and cathode are relatively far apart), suggesting that the hypothesis of Golgi tendon organ stimulation is considered more plausible [123]. By selectively targeting the tendon with electrical current, tendon electrical stimulation does not excite extraneous muscles or motor nerves and does not produce actual joint movement. This property is advantageous for providing force feedback when the user's range of motion is restricted [124]. As described in Section IV-A, EMS can present a force sensation of opposing force when the user attempts to actively resist the induced muscle contraction. In contrast, tendon electrical stimulation, which elicits little to no muscle movement, is suitable for presenting passive force sensations within a confined range of motion.

1) Applications: The main application area of tendon electrical stimulation is force presentation interfaces, and numerous such interfaces have been proposed. For example, stimulating the dorsal wrist tendons has been shown to induce the perception of a force directed from the back of the hand toward the palm [123], [124]. However, tendon electrical stimulation at the wrist has individual differences in how users interpret the induced sensation. Some experimental participants perceive it as a force pushing the entire arm from the dorsal side, while others perceive it as the wrist being flexed dorsally [125]. To address this ambiguity, they integrated tendon electrical stimulation with a head-mounted display visually showing a virtual object pushing the back of the hand [125]. Because tendon electrical stimulation alone sometimes results in subjective differences in how the force is interpreted, it is particularly well suited for scenarios that can be combined with visual or other feedback modalities. Other VR systems have used tendon electrical stimulation at the wrist to present the hardness or viscosity of virtual objects [126]. This system combined fingertip electrotactile pulses that push back during penetration with flexor-tendon currents that pull forward during withdrawal, each scaled linearly to the finger's displacement. Boosting the gain in this current-to-distance mapping made pressing feel stiffer and release feel stickier, enabling purely electrical cues to convey both hardness and viscosity. Another research applied to the fingers to convey force sensations when contacting objects in 3D user interfaces [127].

Tendon electrical stimulation interfaces have also been explored for the lower limbs. For instance, one system designed to provide a realistic sensation of walking in a virtual environment for seated users combines visual and auditory stimuli with electrical stimulation of the ankle tendons (Achilles and tibialis anterior muscle tendons) [128]. Another approach stimulates four tendons around the ankle (Achilles, tibialis anterior muscle, flexor digitorum longus, and peroneus longus tendons) and has demonstrated that anteroposterior and lateral illusions of body sway can be induced [129]. This technique has been applied to VR locomotion techniques to provide a sensation of ascending or descending virtual slopes [130], [131].

2) Stimulation devices: Tendon electrical stimulation, similar to nerve bundle stimulation and EMS, involves placing anodes and cathodes on the skin surface above the target tissue. Focusing current on the tendon is preferable to avoid inadvertently activating other nerves or muscles. Therefore, inspired by previous works on vibration stimulation of tendons, parameters such as current frequency have been adjusted accordingly [129].

V. General Discussion

In this review, we introduced four types of TENS methods for haptics: electrotactile stimulation, nerve bundle electrical stimulation, EMS, and tendon electrical stimulation. In this section, we first discuss the validity of this classification (Section V-A). Then, based on the classification of TENS methods for haptics, we highlight several issues in this field and discuss directions for future research (Section V-B – Section V-F).

A. Validity of the classification

We classified research on TENS methods for haptics into four categories: (1) electrotactile stimulation, (2) nerve bundle electrical stimulation, (3) EMS, and (4) tendon electrical stimulation. We adopted the stance that haptics can be split into tactile and kinesthetic sensations [6], and we further subdivided these based on the mechanisms of haptic presentation. In fact, the literature that we collected was quite straightforwardly classified into one of four categories. There was only one paper [21] for which we were uncertain whether to categorize it into electrotactile stimulation or to introduce a new separate category under kinesthetic presentation. This was because, in

TABLE II
THE RELATIONSHIP BETWEEN ELECTRICAL STIMULATION METHODS AND THEIR APPLICATION DOMAINS. IN THIS TABLE, ONLY THE STUDIES INTRODUCED IN THIS REVIEW ARTICLE ARE CATEGORIZED.

Application domains	Electrotactile	Nerve bundle	EMS	Tendon
Medical care / Rehabilitation		[63]–[68], [68], [69], [69]–[71]		
Accessibility	[37], [38], [43]			
Motor assistance / Skill training		[59]	[79], [87], [89], [90]	
VR / AR / MR	[34]–[36]		[80], [99], [100], [109]	[125], [126]
Daily living support / Wearable interface	[39], [40], [42]	[60]	[88], [91], [108]	

our reading, it primarily stimulates cutaneous receptors, even though the induced sensation is close to kinesthetic. Overall, this classification method comprehensively categorizes TENS for haptics without overlap or omission, thus demonstrating a reasonable degree of validity.

B. Combined electrical stimulation

Table II illustrates the relationship between electrical stimulation methods and their application domains. This figure suggests that the applicable domains differ depending on the characteristics of each electrical stimulation technique. As noted in the caption, this table categorizes only the studies cited in this paper. For example, while the cell for the application of EMS in medical care / rehabilitation is left blank, studies in this domain do exist if one does not limit the scope to TENS for haptics. Although they have different characteristics and applied domains, all of these methods share the important properties of TENS, namely a small and lightweight form, high responsiveness, and low power consumption. These properties make it appealing to combine multiple TENS methods for more complex haptic interface. For example, sports skill transfer requires real-time instruction, and the high responsiveness of TENS makes it a promising option. Furthermore, because sports involve learning skills with the entire body, presenting multiple sensory modalities (both tactile and kinesthetic) may be especially useful, suggesting that combined electrical stimulation could be beneficial. Some small studies have explored combining multiple TENS methods. For instance, one study integrated electrotactile stimulation with EMS to provide both tactile and force sensations, enabling users to feel the sensation of tapping a virtual object [132]. Notably, this study confirmed that simultaneously delivering these two distinct modalities is essential. Achieving such precise timing is likely an advantage of combining TENS methods, given they can be highly time-synchronized.

Two challenges must be addressed to establish combined electrical stimulation. The first is ensuring the independence of the induced sensations. For example, EMS for kinesthetic presentation can inadvertently trigger cutaneous tactile sensations [133], which interfere with the intended sensory output. However, few studies explicitly report such side effects, hindering progress in developing combined electrical stimulation. Future research should actively investigate and report side-effect sensations. Numerical simulations (e.g., finite element methods) to determine stimulation parameters that selectively excite only the target tissue [134] may also help mitigate this problem.

The second challenge is electrode placement. In particular, if two stimulation methods require electrodes in close proximity, they may interfere with each other. Figure 3 illustrates the approximate placement for each type of TENS method. As an example, EMS and nerve bundle electrical stimulation at the wrist can be very close, potentially causing electrode interference. Consequently, it may be necessary either to select methods whose electrodes do not overlap or to use multi-electrode arrays capable of switching among nearby stimulation sites.

Combining multiple TENS methods that share advantages such as lightweight, high responsiveness, and low power consumption could be particularly applicable to movement tasks requiring agility, such as sports. We anticipate that such combined TENS will significantly expand the capabilities and applications of haptic interfaces in the future.

C. Need for qualitative evaluation

As is often stated, hands-on experience is crucial in haptics research, making it difficult to convey the quality of the experience through text or images. Nonetheless, qualitative evaluations of user experience remain comparatively scarce in the field of TENS. For example, EMS [109] and tendon electrical stimulation [128] have both been utilized to present a natural walking sensation. However, these are fundamentally different phenomena, likely leading to qualitatively distinct perceptions. Nevertheless, they are grouped under the same label of "natural walking sensation." A potential solution is to conduct qualitative assessments, such as interviews. One example of qualitative evaluation in TENS research used explicitation interviews to investigate changes in perceived sensations under different stimulation parameters [135], reporting that words like "pushing," "tapping," "impulse," "pressing," and "pulling" were used differently for each parameter. These differences suggest that the quality of the perceived sensation changes with stimulation parameters. Conducting such qualitative evaluations could uncover subtle differences not captured by quantitative assessments, thereby enhancing scientific rigor of this field.

D. Risk of confusion from identical terminology in different stimulation methods

In this review, we distinguish two types of TENS methods for presenting tactile sensation: electrotactile stimulation and

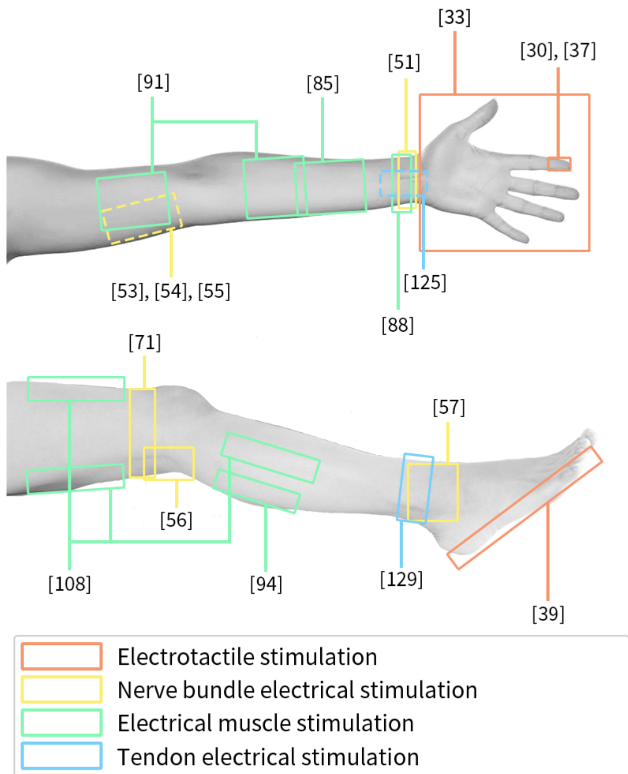

Fig. 3. Distribution of stimulation sites for each transcutaneous electrical stimulation method. The numbers in the figure correspond to the reference numbers in the article.

nerve bundle electrical stimulation, following the conventional terminology used in the field. The former targets mechanoreceptors in the skin, whereas the latter targets afferent nerve bundles. As previously noted, this distinction is not widely recognized. Therefore, research that stimulates nerve bundles for tactile feedback sometimes uses the term "electrotactile stimulation." During our literature review, we identified some studies of upper-limb amputees and prosthetic users that employed a stimulation device originally intended for mechanoreceptor-oriented methods [136]. Because cutaneous stimulation near the electrode induces tactile perception at the same location, using such a device for prosthetic hand feedback is not implausible. However, nerve bundle electrical stimulation aims to provide tactile feedback in the phantom hand region of amputees by stimulating the remaining afferent nerves [62], [75]. In other words, these are fundamentally different approaches, yet both are commonly referred to as "electrotactile stimulation," which can be confusing. To address this issue, we propose an alternative naming scheme. Specifically, we refer to the method introduced in III-A (electrotactile stimulation) as "local electrotactile stimulation", and the method introduced in III-B (nerve bundle electrical stimulation) as "remote electrotactile stimulation". This terminology is new and not yet widely known in the field, but it accurately captures the phenomenon of the both methods. Another approach may be to conduct comparative qualitative research by letting upper-limb amputees who are potential end-users directly experience and describe both cutaneous receptor targeting methods and nerve-bundle targeting methods to clarify the differences in perception. Because only amputees themselves can articulate the subtleties of their phantom limb sensations, if these experiences are qualitatively distinct, that distinction should be widely recognized by the research community to avoid confusion.

E. Toward practical interface research

While EMS and nerve bundle electrical stimulation are relatively well-developed for medical applications, their use outside of medicine (e.g., in general haptic interfaces) has not advanced significantly. A rare example of commercialization is the "PossessedHand" [83], [84]. However, the practical use of TENS still lags behind other haptic methods, such as vibration. One obstacle to its adoption is safety concern. The safety guideline of TENS is studied [137], and it has become widely known among researchers. However, in an interview study on user acceptance of electrical stimulation devices, participants often expressed reluctance to use them due to perceived (and sometimes unfounded) fears of danger [138]. This study highlights that participants' anxiety stems from concerns such as the potential for irreversible health effects and the unknown consequences of long-term use. Therefore, thorough safety evaluations and broad societal acceptance of TENS are critical for practical deployment of TENS interfaces.

Reducing barriers to routine use is also important. For example, the smartwatch-based EMS device [88] introduced in Section IV-A1 leverages a widely adopted wearable platform, requiring minimal additional setup. Because TENS is light, compact, and power-efficient, it is ideally suited for integration into wearable devices [139]. Research efforts that incorporate such stimulation into everyday wearable devices might be an essential step toward widespread, user-friendly adoption.

F. Individual differences in sensory perception

Individual differences in the perceived sensations are a recognized challenge for electrotactile stimulation, nerve bundle electrical stimulation, EMS, and tendon electrical stimulation [140]–[142]. Particularly with tendon electrical stimulation, users may vary in how they interpret the induced force [125], [130], adding complexity to consistent perception across individuals. The number of participants is limited, but individual differences in the effects of tendon electrical stimulation are also studied [142]. The results revealed gender-related differences and age-related correlations in female participants, while no significant relationships were found between effects on electrical stimulation and biostructural metrics such as body weight or fat percentage.

Efforts to address this issue include various calibration methods [141], dynamic adjustment of stimulation position [115], and use of suitably sized electrodes [143]. A calibration method that automatically adjusts the stimulation current at a single stimulation point by combining real-time measurement of skin impedance with random forest regression has also been studied [144]. Because individual differences pose a common problem across all types of TENS, it may be beneficial to apply solutions developed for one method (e.g., the dynamic electrode placement algorithm for EMS) to others (e.g., nerve bundle electrical stimulation).

VI. Conclusion

In the first half of this paper, we reviewed four TENS methods for haptics (electrotactile stimulation, nerve bundle electrical stimulation, EMS, and tendon electrical stimulation), focusing on mechanism and properties, applications, and stimulation devices (Sections II, III, and IV). In the second half, we examined the issues that emerge when classifying TENS methods for haptics into these four types and discussed directions for future research (Section V).

This review makes two key contributions. First, it categorizes haptics-related TENS methods into four groups, providing an overview of existing research. Previously, no single review covered the entire breadth of TENS for haptics, making it challenging for novice learners to gain a holistic view of this field. The classification was designed based on the structure of haptics [6] and on underlying mechanisms of electrical stimulation. We confirmed the classification reasonably and comprehensively group the current research landscape (Section V-A). Hence, this review may serve as a helpful starting point for those seeking an overview of the field. Second, by reviewing TENS methods for haptics based on the classification, we derived insights into future research directions (Section V-B) and issues that warrant attention (Sections V-C – V-F). These insights may help new and established researchers refine and recalibrate their research directions. Consequently, we hope that this review will be a valuable resource for advancing the field of TENS for haptics.

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