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Shape memory alloy actuators for haptic wearables: A review

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ABSTRACT

Devices delivering sophisticated and natural haptic feedback often encompass numerous mechanical elements, leading to increased sizes and wearability challenges. Shape memory alloys (SMAs) are lightweight, compact, and have high power-to-weight ratios, and thus can easily be embedded without affecting the overall device shapes. Here, a review of SMA-based haptic wearables is provided. The article starts with an introduction of SMAs, while incorporating analyses of relevant devices documented in the literature. Haptic and SMA materials fields are correlated, with haptic perception insights aiding SMA actuator design, and distinct SMA mechanisms offering diverse haptic feedback types. A design process for SMA haptic wearables is proposed based on material-centered approach. We show SMAs hold potential for haptic devices aiding visually impaired people and promise in immersive technology and remote interpersonal haptic communication.

1. Introduction

The term "haptic" refers to the sense of touch [1]. Studies on haptic perception originated in the field of physiology pioneered by Weber in the late 19th-century [2]. After that, researchers started to use haptic technologies for teleoperation [3], such as Goertz and Thomson's teleoperation robot developed for nuclear environments [4]. These machines enabled operators to feel the contact force encountered by the end effectors when they manipulated the control devices [5]. Such devices are often referred to as "force displays", which dominated the haptic field until the mid-1990s [3]. Relevant products include *GROPE* [6], *PHANToM* [7], and *CyberGrasp* [8]. The progress in computer science facilitated the integration of haptic technology into numerous commercial fields such as computer-assisted design, medical applications, military, and videogames [2,3,9,10]. Concurrently, haptic technologies evolved beyond merely force displays, leading to a growing diversity of applications and interactions. In addition to vibration, which has remained in commercial use to the present day [11], other types of actuators (e.g. pneumatic, ultrasonic, smart materials) have been successively developed.

Researchers are foreseeing low-cost, lightweight, compact, energy-efficient, and highly mobile devices capable of delivering diverse haptic feedback modalities in the near future [3]. However, there remain many challenges in haptic technology development nowadays. On the software side, substantial computational demands associated with complex haptic rendering algorithms and models necessitate the utilization of high-performance computer chips [3,12,13]. On the hardware side, there is a trade-off between the quality of actuators and bulkiness [3]. The "quality" refers to the volume, weight, flexibility and richness of the haptic feedback types that the actuators can provide. For example, despite vibration actuators are small and lightweight, they cannot provide haptic feedback such as pressing or squeezing. In contrast, pneumatic actuators generate haptic sensations through alternating pressurization and depressurization of chambers [14–16], yet their size and dependency on air pumps make them less compact.

To address these challenges, the incorporation of smart materials into the haptic field has emerged as a promising approach. Smart materials are materials which can be active and responsive to various stimuli, such as temperature, electricity, magnetism, humidity, and light [17]. They have the potential to facilitate the development of innovative haptic interfaces through various means. On the one hand, some smart materials can be employed in designing flexible sensors or electronic components that conform to the skin's compliance [18–20], which can improve mechanical transmission and promote ergonomic comfort [21]. Several literature reviews address these aspects specifically. For example, Yang *et al.* provided an overview of current active materials-

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based sensors and actuators for haptic technologies in virtual (VR) and augmented reality (AR) [22], while Yin *et al.* also concentrated on VR and AR systems [23]. Biswas and Visell highlighted the potential of emerging materials (e.g. organic electronic materials and carbon nanomaterials) to enable high mechanical flexibility in haptic devices [24]. Moreover, Ho *et al.* reviewed the advancement in material designs for electrically driven soft actuators [25]. On the other hand, some shape-changing materials (e.g. electro active polymer (EAP) [26,27], shape memory alloy (SMA), magnetorheological fluid (MRF) [28,29]) can function as actuators in haptic systems, and generate rich haptic feedback types.

SMA has been used in a range of wearable devices. Based on their functionalities, these wearables can be categorized into two main types: assistive devices and haptic devices. Assistive devices refer to the applications which are developed to aid people with disabilities in performing functions [30], or maintain users' physical functions in extreme environments. For example, Xie *et al.* developed an elbow exoskeleton with SMA springs [31], while Ali and Kim designed a small-scale knee exoskeleton [32]. For more research about SMA wearable exoskeletons refer to [33–36]. Rehabilitation is another type of assistive devices, with relevant research found in [37–39]. Nair and Nachimuthu reviewed SMA applications in the medical field, where they also documented some assistive devices such as wearable exoskeletons and SMA prostheses [40]. Moreover, SMA can be used to develop smart garments to support astronauts' cardiovascular systems [41,42]. Compared with SMA assistive devices, there is less research about wearable haptic devices, most of which are developed as VR and AR devices, or notification interfaces. Srivastava *et al.* analyzed the recent research work in the field of SMA-based smart wearables, followed by a discussion regarding the diverse applications of SMA in human-robot interaction and industry 5.0 [43]. Their review article only provides limited coverage of SMA haptic wearables.

This paper reviews opportunities of SMA wire-based actuators concentrating on wearable haptic devices, which is currently absent in the intersection field of smart materials and haptic. SMA wires contract reversibly when heated. They are flexible, lightweight with small volume and thus offer opportunities for diverse haptic feedback types in wearable applications. This review mainly aims at interaction designers and researchers with a focus on haptics in the HCI community. Relevant literature is collected from different databases including ACM Digital Library, IEEE Xplore Digital Library, Scopus and SpringerLink. Literature is analyzed from various aspects like working performance, haptic feedback types, mechanism types, and application fields.

This article is structured as follows. First, working principles, performances, and important features of shape memory alloys are introduced in section 2. Then, the correlations between haptic and SMA material fields are elucidated, within which different SMA mechanisms and their provided haptic feedback types are emphasized. In section 4, haptic wearables documented in existing literature are classified and reviewed, along with an analysis of their reported user studies. Finally, a design process for SMA-based haptic wearables and future applications are proposed in the discussion and outlook section.

2. Shape memory alloys (SMAs)

2.1. SMA working principles

SMAs are metals which can return to their initial shapes after training. There are many types of SMAs, with the nickel-titanium (NiTi) combination as the most frequently used alloy. SMAs usually are activated with heat, supplied either by their thermal environment or by applying an electrical current (the Joule heating effect). Activated SMAs have a much higher modulus than the SMAs in non-activated states. They can reversibly contract and stretch during heating and cooling [17]. In an actuator system, the SMA wires must be connected to an element which provides the counter force to restore the actuator to its initial state. Two types of actuator systems are often used in SMA devices. As shown in Fig. 1(a), an SMA wire is connected to a fixed point on one side, whereas on the other side, it is connected to an elastic spring. The actuator point (called effector) is at the connection of SMA and elastic spring. When the SMA wire is heated above its transition temperature, it contracts and pulls the effector to move. With the temperature dropping, the actuator point is pulled back by the elastic spring. Such a mode can be called *displacement mode*. The phase transformations, that are responsible for the observed plastic behaviour, occur due to changes in the atomic structure [44]. If an SMA wire is fixed between two stationary points and the displacement is blocked (see Fig. 1(b)), the force on the stationary points increases with increasing temperature, as the SMA wire tries to contract at high temperatures [45,46]. This is therefore called the *force mode*.

An SMA actuator system which shows reversible actuation is said to show *shape memory effect (SME)* [45]. *Displacement mode* exhibits reciprocating motion, whereas *force mode* generates alternating force during heating and cooling, and thus these two modes can refer to as SME. If SMAs have transition temperatures sufficiently below room temperature (e.g. below 0 ℃), they show the so-called *super-elastic/ pseudoelastic effect (SE)*. *Super-elasticity* refers to the large (up to 8%) recoverable deformation of the SMAs when loaded at room temperature. Although after loading, an SE material is able to return to its initial position. The mechanical response differs from a pure elastic material in that loading and unloading curves follow different trajectories (Fig. 1(c)) [45,48]. Superelastic wires are often used as counter springs to help reset the SMA wires in actuator constructions.

SMAs are low-cost and reliable [17]. They have been used in many different fields with aerospace as one of the most prominent domains. Examples include *Mars Global Surveyor* and NASA's superelastic NiTi-based wheels for future moon and Mars missions [49]. SMAs also have potential in the development of adaptive aircraft wings [50,51]. Owing to the excellent *Magnetic Resonance Imaging (MRI)* compatibility and corrosion resistance [45], SMAs are also broadly adopted in medical products, such as nitinol stents [52] and orthodontic applications [53]. In the smart textile domain, SMAs can be used to design a smart insulation system for regulating the thermal insulation effect of the garment [54]. SMA can also be used in flexible "*Woven Patches*" interfaces, offering new ways to interact when integrated with clothes or applied directly to the skin [55].

2.2. SMA working performances in haptic devices

(1) Actuation stress / force

A commonly used approach to determine the actuation force involves performing tensile tests on SMA wires or strips to obtain stress–strain curves for both the martensite and austenite phases at low and high temperatures. The tensile tests intend to elongate the SMA wires at pre-set temperatures. More details about experimental setup and testing procedures can be found in the ASTM standard [56].

Typical SMA stress–strain curves are shown in Fig. 2. The curves in high-temperature environments have higher plateau stress levels. Regarding the *Force Mode* (see Fig. 1(b)), the displacement of SMA is fixed during actuation. Hence, a constant strain line (vertical green dashed line in Fig. 2) can be plotted to get the intersection points with stress–strain curves at different temperatures. The difference between the stress values at each two intersection points is the actuation stress at the corresponding two temperatures. It can be seen that the actuation stress is related to the constant strain as well as the temperature. For a given SMA actuation system, the actuation force would be larger if it is placed in a warmer environment.

Actuation stress of a pre-stretched Nitinol wire is reported to be 100–500 MPa [57,58]. It means that a 0.1 mm diameter pre-stretched NiTi wire of 20 cm long and of 0.01 g weight can exert a force of about 0.78–3.93 N. The fact of being compact, and lightweight with high

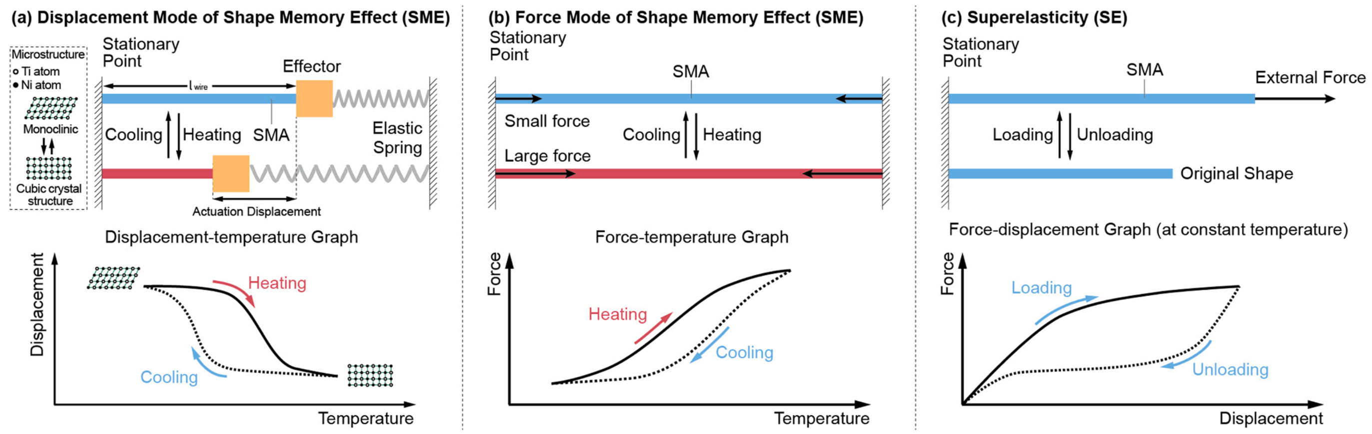


Fig. 1. (a) SMA microstructure, displacement mode and displacement-temperature graph. (b) SMA force mode and force-temperature graph. (c) Superelastic/pseudoelastic effect (SE) and force-displacement graph [17,47].

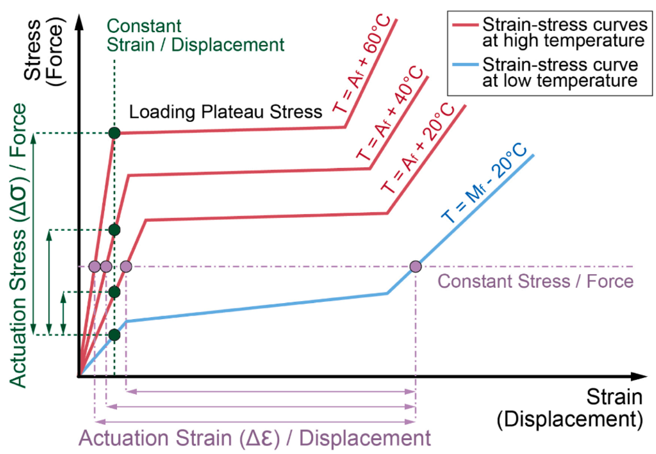


Fig. 2. Actuation stress and strain can be obtained with the stress–strain graph [45].

power-to-weight ratio makes SMAs to be a good candidate for wearable haptic devices.

Most wearable SMA haptic devices reported in literature operate at force levels less than 3 N. Examples are *FingerFlex* (up to 1.6 N) [59], *SCWEES* (about 1 N) [60], and the haptic glove of Terrile *et al.* (1–3 N) [61]. It should be noted that the actuation force of SMA wires itself can differ from the actuation force of the overall haptic devices due to the design of the actuator structures. For instance, Jones *et al.* designed an SMA tactor unit which comprises a pin, pivot rod, SMA and superelastic wires (see Fig. 4 (a)) [62]. When it is activated, the pin rotates around the pivot rod which presses against the skin of the user's torso. The peak force of the actuator ranges between 5 and 9 N [62]. Other ways to increase the force are to combine more SMA wires, distribute wires in parallel, or knit them together. The SMA knitted actuators developed by Eschen *et al.* can generate a force up to 9 N [41]. A disadvantage of the knitted actuators is that they are less compact (see Fig. 3 (d)).

(2) Actuation strain / displacement

The actuation strain can also be derived from the stress–strain graph. As shown in Fig. 2, a horizontal constant stress (purple dot-dashed line) can be plotted to obtain the intersection points, so that the actuation strains can be calculated with the differences of strain values at corresponding temperatures [45].

The term "*displacement amplification factor* (f)"is used to refer to the ratio of the actuation displacement produced by the actuator to the length of the actuator. For an actuator constructed by a bare SMA wire, its *displacement amplification factor* is equal to the actuation strain $\Delta\varepsilon_{wire}$ (see purple caption in Fig. 2):

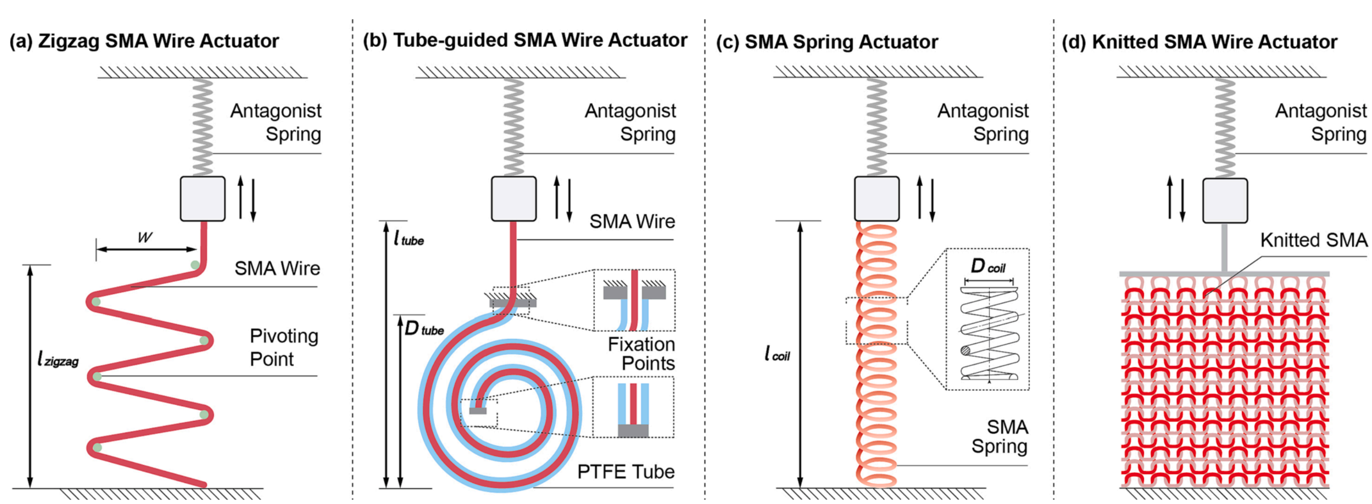


Fig. 3. Constructions for increasing the actuation displacement: (a) Zigzag SMA wire actuator. (b) Tube-guided SMA wire actuator. Note that the tube can be winded in a same diameter circle or in spiral. If it is in spiral, the Eq. (3) needs to be redefined. (c) SMA spring coil actuator [65]. (d) Knitted SMA wire actuator.

$$f_{wire} = \frac{\delta^L_{wire} - \delta^H_{wire}}{l_{wire}} = \Delta\varepsilon_{wire} \quad (1)$$

where δ^L_{wire} and δ^H_{wire} is the displacement of SMA wire at low and high temperature respectively, l_{wire} is the original length of SMA wire.

SMA wires of the Nitinol type have a maximum actuation strain of around 4–8% of the total length (e.g. 4 cm for a 1 m SMA wire), meaning that the *displacement amplification factor* of the bare SMA mechanism is small. There are several methods to obtain a larger factor value. The first method is to arrange a long SMA wire into a zigzag shape with several pivoting points (see Fig. 3(a)). The *displacement amplification factor* of such a mechanism depends on the number of the pivoting points and their lengths:

$$f_{zigzag} = f_{wire}\sqrt{1 + \frac{W^2 N^2_{zigzag}}{l^2_{zigzag}}} \quad (2)$$

in which l_{zigzag} is the length of SMA zigzag actuator, N_{zigzag} is the number of pivot points, W is the horizontal width of the zigzag actuator (Fig. 3(a)).

The second option is the tube-guided SMA wire actuator. As can be seen in Fig. 3(b), a long SMA wire is inserted into a plastic tube, which can be rolled up and only needs two fixation points [63,64]. For the first fixation point which is situated near the effector, only the tube is secured, permitting the entire SMA wire to extend within the confines of the tube. Regarding the second one, the tube and SMA wire are connected at their extremities. When the SMA wire is activated, it contracts inside the tube, subsequently causing the motion of the effector. For the tube-guided SMA wire actuator, the *displacement amplification factor* can be defined as:

$$f_{tube} = f_{wire}\left[1 + \frac{D_{tube}(N_{tube}\pi - 1)}{l_{tube}}\right] \quad (3)$$

where it is assumed that the tube is stacked on top of each other for every subsequent winding cycle, N_{tube} is the cycle number, D_{tube} is the diameter of the winding circle, l_{tube} is the original length of the tube-guided SMA wire actuator.

An application example of the tube-guided SMA wire actuator is shown in [64]. A soft 2-axis haptic navigation demonstrator consisting of 4 tube-guided SMA wire actuators (each with length 50 cm) can generate displacements of about 20 mm, whereas the dimension of the whole device is only 17 × 17 cm (see Fig. 5(c)) [64].

The third actuator structure is a SMA spring coil, which can also generate larger displacement in comparison with the SMA wires. However, the increase of actuation stroke for spring coil actuators comes with a decrease in actuation force. The *displacement amplification factor* of an SMA coil spring is given by [66]:

$$f_{coil} = \frac{\delta^L_{coil} - \delta^H_{coil}}{l_{coil}} = \Delta\gamma_{coil}\frac{\pi N_{coil} D^2_{coil}}{d l_{coil}} \quad (4)$$

where δ^L_{coil} and δ^H_{coil} are the coil spring displacements at low and high temperatures, l_{coil} is the free length of the SMA spring, D_{coil} is the mean coil diameter, N_{coil} is the active coil number, d is the SMA wire diameter, $\Delta\gamma_{coil}$ is the actuation shear strain which can be obtained with shear stress–strain graph (similar to Fig. 2). More detail is depicted in Fig. 3(c).

Knitted SMA wire actuators (see Fig. 3(d)) are also an option which can provide large displacement and force, but they are difficult to manufacture in comparison with other methods. The actuation displacement of knitted SMA is complex and depends on details of the knitted structure. Relevant research can be found in [41,67,68].

A high *displacement amplification factor* indicates that an actuator with a short length can generate large actuation displacement. The formula for each SMA construction reveals the parameters influencing its *displacement amplification factor*. By comparing these formulas, an optimal structure can be chosen for a specific coverage area. For example, in a 5 × 2 cm area aiming for 10 f_{wire}, the zigzag SMA wire actuator requires 25 pivoting points (N_{zigzag}), while the tube-guided SMA actuator only needs 8 winding cycles (N_{tube}). In this scenario, the tube-guided SMA wire actuator is easier to design in a small size.

(3) Actuation time

Actuation time refers to the time taken for a single actuation cycle, i.e. the time needed for actuation (during heating) and returning to the initial state (during cooling). For the actuation time of SMA actuators, it is reported from 0.5 s to 30 s in the literature [69].

Heating can be achieved by changing the environmental temperature, but for wearable devices, actuation is achieved by Joule heating of the SMA wire. Since the electrical resistivity (ρ_R) of SMA is rather high (0.5–1.1 × 10^{-6} Ωm), it is easy to heat the wire by applying an electric current [45]. The energy needed to heat a wire of length (L) and diameter (d) is given as:

$$E_w = \frac{\pi}{4} d^2 L \rho C_p \Delta T \quad (5)$$

where ρ is the density of the SMA wire, C_p is the heat capacity per unit mass (assumed constant), and ΔT is the difference between ambient temperature and the required actuation temperature.

The energy supplied by the Joule effect is:

$$E_n = I^2 \rho_R L t_{heat} \quad (6)$$

in which I is current, ρ_R is the electrical resistivity, L is the length of the SMA wire, t_{heat} is the heating time.

If the heat loss to the environment is neglected, the heating time to obtain a required temperature can be calculated with Eq. (5) and (6) as:

$$t_{heat} = \frac{\pi d^2 \rho C_p \Delta T}{4 I^2 \rho_R} \quad (7)$$

It can be seen that the most efficient way to reduce the heating time is by increasing the applied current. However, it is much more difficult to reduce the cooling time because the cooling rate is limited by the heat transfer rate to the surrounding environment [70]. It is estimated that for a 0.2 m long 0.5 mm diameter SMA wire and a required temperature change of $\Delta T = 65$ ℃, about 6 s is needed for heating, while the cooling process lasts for 40 s [45].

A reduction in cooling time can be achieved by using thinner wires, enhancing airflow [71], or using wires with higher actuation temperatures which have a faster initial cooling rate. Studies indicate that a 0.4 mm diameter SMA wire with a length of about 0.2 m experiences a cooling time of approximately 7 s when subjected to airflow of 20 l/min. In contrast, the same wire takes about 20 s to cool down in the absence of airflow [72]. Circulating cold fluid with a high thermal conductivity around SMA is another effective way [70]. Nevertheless, incorporating either airflow or cold fluid techniques adds weight and volume to the SMA haptic devices, potentially compromising the comfort of wearable devices. Moreover, the airflow approach might generate noise. The cold fluid technique necessitates proper sealing, and the presence of a liquid tank could restrict user mobility.

An antagonist SMA wire can be used which actively helps in restoring the actuator to its initial position (e.g. *SCWEES* (see Fig. 4(b)) [60]), and thus reduce the actuation time. This method will bring some challenges to mechanism design. For example, in Fig. 4(b), when the red SMA wire is actuated, two effectors are pulled apart (see red arrows). If they are expected to move back to their original positions by activating the blue SMA, it is necessary to ensure the force generated by the activated blue SMA is higher than the red one. Note that at the switch moment, the red SMA is still at a high temperature and needs time to cool, which means that the red SMA is still very stiff.

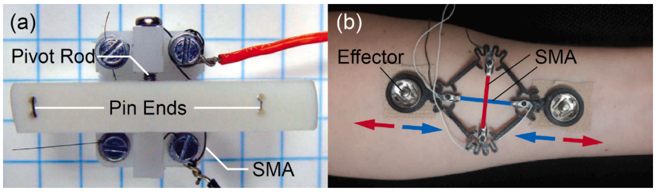


Fig. 4. (a) SMA tactor unit: two ends of the pin are fixed with a SMA and superelastic wire correspondingly. The pin can rotate around the pivot rod when the SMA is actuated, and generate pressure on skin. [62]. (b) *SCWEES*: working principle can be seen in of Table 2(d1) [73].

(4) Energy EfficiencyIn the case of Joule heating, the energy consumption of SMA actuators mainly depend on geometric dimensions (e.g. cross-sectional area, total length) and transformation temperatures. The input energy can be calculated with:

$$E_{in} = \rho_R \frac{L}{d} I^2 t \tag{8}$$

in which E_{in} is the input energy, t is the actuation time.

Output work can be obtained with:

$$W_{out} = FS \tag{9}$$

where W_{out} is the output work, F is the force exerted by the SMA actuator and S is the actuation displacement.

With Eq. (8) and (9), the energy efficiency can be derived:

$$\eta = \frac{W_{out}}{E_{in}} \times 100\% \tag{10}$$

The maximum energy efficiency of SMA actuators are reported in a range of 10–15% in the literature [74–76], which is a relatively low value in comparison with other types of actuator (e.g. vibration actuators). Note that the main reason for this low efficiency is the fact that it requires a continuous supply of energy to keep the actuator in its actuated state. Energy consumption can be reduced by introducing a latch mechanism. For example, Haga *et al.* developed a dynamic braille pin display, in which a magnetic latch mechanism can fixate the pins in their up/down positions and power consumption is decreased because the driving current can be turned off after actuation [77].

(5) Performances in bending mode

Pre-trained SMA wires in curve shapes are also able to generate actuation force when heated. However, for a given SMA wire, the actuation force in the bending mode is much lower than in the elongation mode. Large-diameter SMAs are often used to increase the actuation force of a bending actuator. For instance, Tobushi *et al.* presented a reversible composite actuator by embedding a 0.75 mm diameter SMA wire (with a length of 50 mm) in shape memory polymer [78]. Three-point bending flexural experiments show that the maximum actuation force is 13.6 N. In the elongation mode, however, a 0.75 mm diameter SMA wire could have generated an actuation force of 44–220 N according to the actuation stress reported in the literature [57,58]. More information about SMA bending properties can be found in [79–81].

There are only a limited number of SMA wearable haptic devices using the bending actuation mode [82]. Large diameter wires will make the haptic devices stiff and uncomfortable to wear, and they need more time to cool down. An advantage of the bending mode is that it can be achieved using shorter wire lengths, which may result in reduced energy consumption.

(6) Lifetime

Lifetime prediction is crucial for engineering devices which need to be subjected to cyclic mechanical motion. SMA medical devices which are permanently implanted can experience millions to billions of cycles [83]. However, the situation of SMA haptic devices is different, as many medical devices are superelastic applications (see Fig. 1(c)) [84], while most of the SMA haptic devices rely on the *shape memory effect*. Research indicates that superelastic SMA provides longer lives and greater fatigue limits than thermal martensite SMA under stress-controlled conditions [83].

To avoid irreversible damage to SMA integrity and extend the lifetime of haptic devices, the most important thing is to make sure the SMA does not exceed its deformation limit. The safe limitation is affected by many factors, such as materials components and deformation types (e.g. elongation, bending, torsion). For SMA wires in the elongation deformation, it is often recommended to maintain their strain change below 4%, which should be considered when designing SMA haptic devices. For instance, for the navigation device in Fig. 5(c), if the width d is 4 cm, each SMA wire should be 1 m, so that when the wire B is activated, the strain change of wire A is no more than 4%.

Even though the SMA strain is maintained within its safe limitation, it still experiences thermo-mechanical fatigue after undergoing many thermally activated cyclic transformations. Summarized from relevant research, Kang and Song reported that under consistent axial stress, both peak and valley strains progressively rise as the number of thermal cycles grows, and the effect is more pronounced with higher levels of constant axial stress [85]. In addition, the transition temperatures of SMA are also affected after number of thermal cycles [85]. Li *et al.* found that the recovery strain of SMA is affected by the number of cycles [86]. For example, for a SMA wire (annealing at 500 ℃ for 15 min) which is subjected to 310 MPa, its recovery strain decreases from 4.5% to 3.5% at the first 100 heating–cooling cycles, then remains stable from 100 to 20000 cycles [86]. It is possible to obtain a higher stable recovery strain by adjusting the annealing temperature, annealing time and the applied stress [86,87].

Evaluating the lifetime of SMA haptic devices based on existing models is challenging, as it might be affected by the selection of SMA mechanisms, annealing methods, etc. It is suggested to conduct relevant experiments in the later stages of device development to accurately assess the device's lifetime.

Working performances of SMA-based haptic devices are summarized in Table 1.

Table 1
Reported working performances and features of SMA wearable haptic devices in literature.

Characteristics / Features	Reference Values
Actuation Force	0.8–9 N [59–62,88–90]
Actuation Displacement	0.8–20 mm [64,73,91,92]
Actuation Time	0.5–30 s [45,60,69,73]
Energy Efficiency	10–15% [74–76]
Voltage Requirement	1–17 V (1–6.4 A) [64,82,93,94]. It largely depends on the length, diameter and activation temperature of the SMA wire.
Working Temperature	40–100 ℃
Device Sizes References	Finger device: 2.7 × 2.7 × 3 cm^3 [95] Arm device: 17 × 17 cm^2 [64]

2.3. SMA features for wearable haptic devices

(1) Low voltage requirement

A wearable haptic navigation device constructed using a 0.25 mm diameter SMA wire of 50 cm length requires approximately 5.4 V (0.7 A) for activation [64]. For the SMA bending mode, a 1.00 mm diameter SMA wire with a length of 5 cm only requires 1 V to activate. Commonly available batteries are capable of satisfying voltage requirements at this level.

(2) High working temperature

Reaching the activation temperatures of SMA is essential for the proper functioning of SMA-based haptic devices. Activation temperatures of SMA depend on materials composition and thermal annealing conditions [99]. To rapidly activate the SMA, it should have an actuation temperature preferably between body temperature and 100 ℃. In addition, when using SMA wires with high activation temperatures in wearable haptic devices, it is necessary to implement thermal insulation to protect the skin from burns. For example, SMA wires can be placed inside plastic tubes or incorporated into textile-based insulation layers.

(3) High flexibility and small form factor

Compared with rigid mechanical structures, SMA wires are thin, bendable and lightweight. Such features make it possible for embedding shape memory alloys into textiles. Textile-based SMA haptic devices eliminate the need for bulky mechanical components, such as motors and pneumatics, thereby probably could offer enhanced aesthetic appeal (see Fig. 5).

(4) Noiseless

In contrast to many other actuators like electric motors, SMA actuators operate with no friction or vibration allowing extremely silent movements [75]. It makes SMAs especially suitable for some communal circumstances such as conference rooms and healthcare facilities, in which users are often required to silence digital devices to prevent disturbances to others.

(5) Excellent corrosion resistance

Corrosion resistance properties of SMA rely on the presence of a passive film on the surface, which forms spontaneously when the alloy comes into contact with an oxidizing environment [100]. SMAs are frequently employed as implant materials and utilized in various medical applications, such as stents, due to their unique corrosion resistance properties. Research shows that the corrosion rate of nitinol in distilled water containing 3.5% *Sodium Chloride* is approximately 34 μm/year [101].

Maintaining the washability of wearable devices is crucial for hygiene, especially when haptic wearables are in direct contact with the skin. SMA haptic devices benefit from the inherent corrosion resistance of SMAs, making them washable. However, to ensure complete washability, water-resistant electronics must also be incorporated. Alternatively, modular designs can be employed, allowing for the temporary removal of electronic components prior to washing.

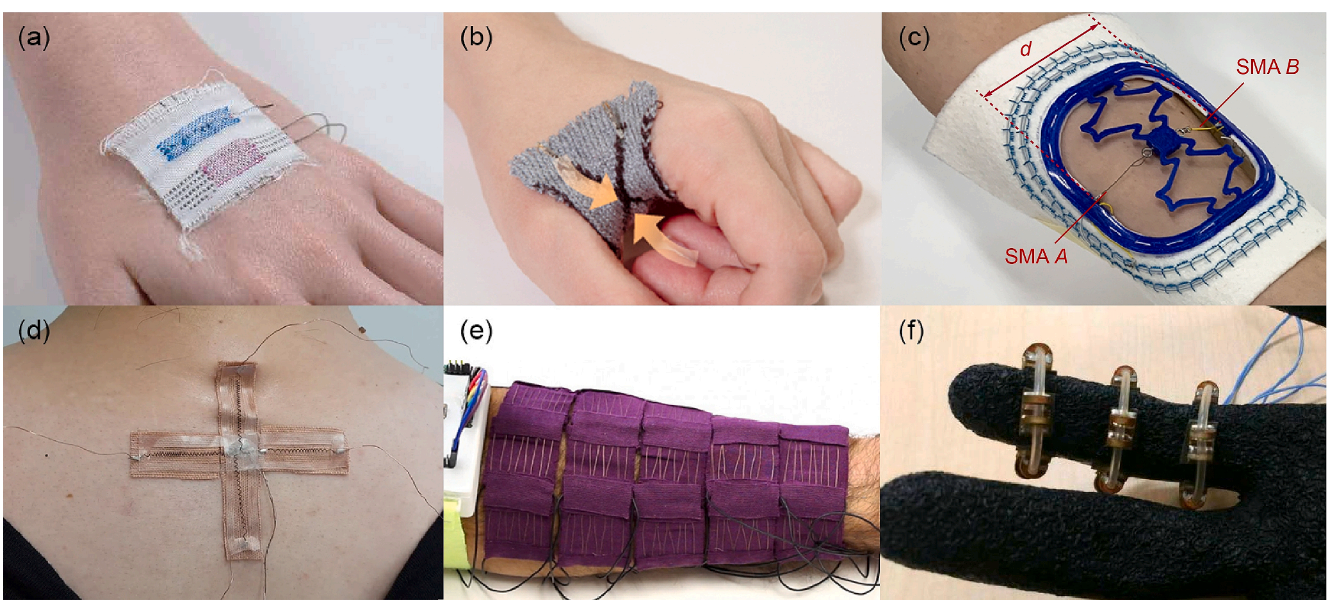


Fig. 5. Shape memory alloy embedded in textiles. (a) A discreet on-skin alarm system [96]. (b) *KnitDermis* [97]. (c) A haptic device for navigation [64]. (d) *Springlet* [98]. (e) *Touch Me Gently* [93]. (f) Haptic device with three SMA rings [91].

3. Neurophysiology and psychophysics of touch in relation to SMA capabilities

3.1. *Haptic perception insights for SMA actuators design: discrimination, sensitivity and affectivity*

Haptic perception relies on two types of systems: the cutaneous and kinesthetic systems [102]. Although both systems are essentially underpinned by nerve cells, they play different roles in humans' somatosensory system. The kinesthetic system is to manage internal signals (e.g. body position, limb direction, and joint angle, etc.) sent from the muscles, tendons and joints about the position or movement of a limb [103]. Receptors of the kinesthetic system are generally embedded in muscle fibers and joints. The cutaneous system is responsible for handling sensations gained from skin sensitivity, including vibration, touch, pressure, temperature, and texture. Despite their distinct functionalities, most everyday haptic perception is a combination of cutaneous and kinesthetic sensations.

From a deeper perspective of neurophysiology, four principal types of mechanoreceptors distribute inside human skin, which are *Pacininan corpuscles*, *Ruffini corpuscles*, *Merkel corpuscles* and *Meissner corpuscles* (Fig. 6) [104]. These corpuscles have different sensibilities for distinct haptic types. For instance, *Ruffini corpuscles* can sense stretch and pressure, while *Meissner corpuscles* have a higher sensitivity to vibration [105]. Once receiving a touch single, massages are conveyed quickly through myelinated nerve fibers, and finally reached and processed by the somatosensory cortex (Fig. 6).

(1) Two-point discrimination threshold

Two-point discrimination threshold is often used to measure tactile spatial acuity. The two points are distinguishable from one only when they are sufficiently separated to evoke spatially distinct neural activity patterns [107,108]. The discernible minimum distance between the two points depends on the skin area, ranging from 1 mm on the tip of the tongue to 68 mm on the back and thigh [109,110]. This threshold is able to guide the design of haptic devices by determining the appropriate resolution and actuator distribution. For skin areas with high tactile acuity, densely packed haptic actuators can provide more realistic and natural haptic feedback. In contrast, fewer actuators are needed for skin with lower thresholds, which can reduce material and manufacturing costs.

Given the SMA characteristics of small size, it is suitable to employ SMAs in high-resolution haptic devices within limited space. Taylor *et al.* showcased this by incorporating a sixty-four-element tactile array in a compact 4 × 2 cm area [111]. Similar studies are referenced in [112,113]. Even though these dynamic braille displays are not wearable devices, SMAs have demonstrated their potential for creating wearables for skin areas with low two-point discrimination thresholds.

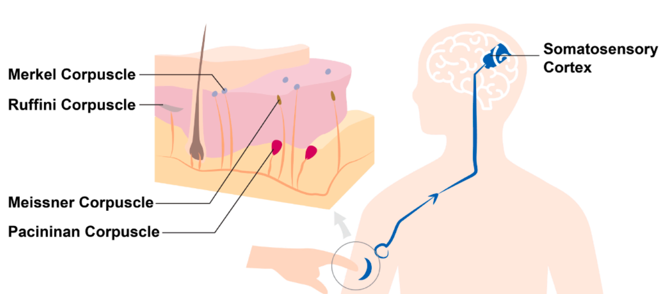


Fig. 6. Haptic perception process basing on cutaneous system [106].

(2) Absolute-thresholds of force perception

Owing to the varying density and distribution of mechanoreceptors in different skin regions, skin at different locations exhibits distinct sensitivity to force, which is referred to *absolute-thresholds* of force perception [114]. Fingertips and facial skin show a heightened responsiveness to tactile sensations [115]. A fingertip has an absolute-threshold of 0.8 mN, while the value is 1.5 mN for the palm [116]. The values can be affected by other parameters like contact area, simulation duration, skin temperature and user age [117]. A sensitivity experiment based on the *Von Frey Monofilaments* method also shows that the forehead and palm can detect the minimum force of 0.07 g, followed by the arm at 0.4 g, and the thigh and shin with a higher threshold of 1.0 g [118]. In reference to section 2.2, the actuation force level of SMAs is sufficient to satisfy the minimum threshold necessary for perceiving tactile stimuli on the skin. However, it also depends on SMA mechanism designs, as the actuation force generated by SMAs often differs from the force experienced by the skin in most scenarios.

(3) Tactile direction discrimination

Tactile direction discrimination measures humans' abilities to differentiate the direction of an object moving across the skin [119]. The discrimination thresholds of the arm, palm, thigh and shin vary from 18 mm to 27 mm [118]. To achieve the desired displacement using a bare SMA wire with an actuation strain of 4%, a length ranging from 45 to 67.5 cm is required.

(4) Temperature Discrimination

Temperature perception relies on two distinct types of thermoreceptors: cold receptors and warm receptors [120]. Cold receptors are up to 30 times more abundant than their warm counterparts, indicating a higher sensitivity to detecting changes in colder temperatures [121]. Warm receptors respond to increasing skin temperatures, with their discharge rate reaching a peak at around 45 ℃ [122]. When the temperature is maintained at 30–36 ℃, individuals typically are not able to experience a noticeable thermal sensation [121].

Commercially available SMAs typically have an activation temperature range of 20–100 ℃. Many existing SMA-based haptic wearables focus on isolating heat during SMA actuation rather than incorporating thermal feedback alongside force feedback. Everyday haptic interactions between individuals inherently involve thermal sensations. In this regard, SMA technology holds an advantage over alternative approaches like vibration or pneumatic systems, as it can potentially integrate both force and thermal feedback for a more comprehensive haptic experience.

(5) CT Afferents for affective touch

Distinct from the discriminative touch, which relies on the four types of receptors illustrated in Fig. 6, *affective touch* is a unique type responding optimally to gentle stroking [130]. This form of touch is conveyed through *C-Tactile (CT)* afferents, predominantly found in hairy skin, and is processed in the insular cortex, an area associated with emotional processing [131,132]. Affective touch is considered to have evolutionary significance due to its critical role in social bonding and attachment [133,134].

Studies indicate that a stroke speed of 1–10 cm/s is generally perceived as comfortable [135,136]. In particular, users tend to prefer a stroking speed of 1–3 cm/s on the arm, shin, or palm for enhanced pleasantness [118]. This information can serve as a guideline for determining the actuation speed of SMA haptic devices, which can be regulated by adjusting the applied voltage.

3.2. Haptic types provided by SMA actuator mechanisms

There are different classifications of haptic types in literature. Morrison *et al.* defined three categories of social touch, which are simple (e.g. tapping), protracted (e.g. pressing), and dynamic (e.g. stroking) [137,138]. Stanley and Kuchenbecker presented several forms of human physical contact, including tapping, dragging, squeezing, and twisting [139]. In order to categorize SMA-based haptic wearables, we identified five distinct haptic feedback types, which are press, squeeze, stroke, pinch, and drag. Visual representations of each haptic feedback type, along with their associated SMA actuator mechanisms, are provided in Table 2.

4. SMA-based wearable haptic devices

4.1. Application fields

Upon reviewing the current literature on SMA-based wearable haptic devices, we categorized their applications into three fields: virtual reality/augmented reality, affective haptics and notification interfaces. Table 3 provides an overview of the existing devices, organized by their respective application fields. *Body location* and *haptic feedback type* offer brief insights into the devices.

(1) Virtual reality/augmented reality

In VR/AR environments, haptic devices convey the physical attributes of virtual objects, such as the shape, mass, texture, elasticity and

Table 2
Haptic Types and Corresponding Mechanisms.

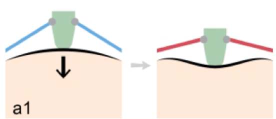
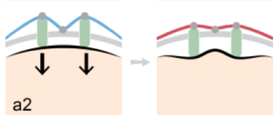
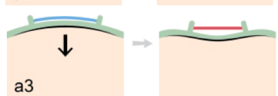
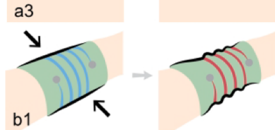
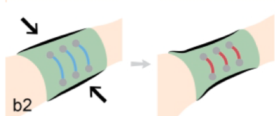
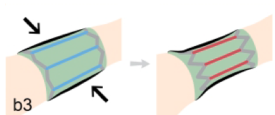
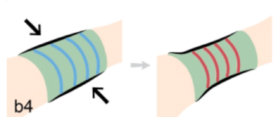
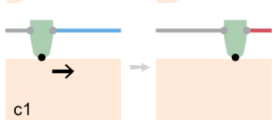
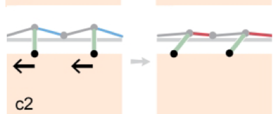
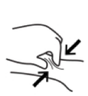
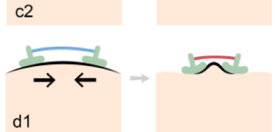
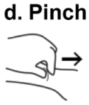
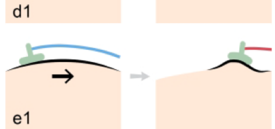
Haptic Feedback Type	Mechanisms	Descriptions	Reference
 a. Press		Two SMA wires/springs are fixed with an actuator point. Upon activation, the SMAs contract and the actuator point moves down.	[62,73]
		The actuator features a pair of actuation points capable of vertical movement, either upward or downward, as a result of temperature changes during the cooling or heating phases.	[123]
		Activation of SMAs induces a bending deformation of the elastic material (e.g. TPU) adhered to the skin. It is essential to avoid using soft textiles, as they may wrinkle and hardly exert pressure on the skin during deformation.	[98]
 b. Squeeze		A long SMA wire that has two fixed ends wraps around a human's limbs or torso.	[124]
		Several SMA springs are fixed on the device in parallel. It should be noticed that the green part material should be soft textile. During actuation, the textile slides on the surface of skin, and it is pulled taut to generate a squeeze sensation.	[125,126]
		The actuator consists of two circular zigzag parts (grey color) and a row of parallel SMA springs. Actuation of the SMA causes deformation of the zigzag part and results in a squeezing movement.	[127]
		Multiple large-diameter SMA wires are pre-trained in an open circle which has a smaller circumference in comparison with the arm. When heated, SMAs tend to roll up, thereby generating a squeeze sensation.	[82]
 c. Stroke		The actuator point is pulled from left to right during the heating process. When it is cooled down, the antagonist spring/elastic band can pull the actuator point back to its original position.	[64]
		A parallel array of actuator points which is perpendicular to the skin before actuation. Once it is actuated, the actuator points are pulled by the SMA, and the tilting movement leads to a stroke sensation.	[128]
 d. Pinch		Two actuator points are fixated on two areas of skin. The part of the skin between the two actuator points is pinched during actuation.	[60,127,129]
 e. Drag		An actuator point is fixated on the skin or fingers. When the SMA is heated, the actuator point is dragged.	[59]

Table 3
SMA-based haptic wearables documented in literature.

Applications	Wearable Haptic Device	Body Location	Haptic Feedback Type
Virtual Reality/Augmented Reality	Lim, B., *et al.* [94]	Fingertip	Press, Shear Force
Virtual Reality/Augmented Reality	Zhang, P., *et al.* [90]	Fingertip	Press
Virtual Reality/Augmented Reality	Esposito, N., *et al.* [156]	Fingertip	Press
Virtual Reality/Augmented Reality	Lim, B., *et al.* [95]	Fingertip	Press, Stroke
Virtual Reality/Augmented Reality	Nakao, Takuro, *et al.* [59]	Finger	Press
Virtual Reality/Augmented Reality	Hwang, et al. [73]	Finger	Press, Shear force
Virtual Reality/Augmented Reality	Terrile, S., *et al.* [61]	Finger	Drag
Virtual Reality/Augmented Reality	Cao, Feier, *et al.* [141]	Hand	Squeeze
Virtual Reality/Augmented Reality	Kim, S., *et al.* [89]	Hand	Press
Virtual Reality/Augmented Reality	Muthukumarana, S., *et al.* [93]	Wrist	Stroke
Virtual Reality/Augmented Reality	Priebe, M., *et al.* [157]	Torso, Arm, etc.	Squeeze
Virtual Reality/Augmented Reality	Nakao, Takuro, *et al.* [158]	Wrist, Ankle, etc.	Press
Affective Haptics	Simons, Melanie F., *et al.* [127]	Wrist	Pinch, Squeeze, Twist
Affective Haptics	Muthukumarana, S., *et al.* [159]	Arm	Stroke, Press, etc.
Affective Haptics	Wang, R., *et al.* [160]	Arm	Squeeze
Affective Haptics	Papadopoulou, A., *et al.* [161]	Arm	Warm Press
Affective Haptics	Kim J. [82]	Arm	Squeeze
Affective Haptics	Duvall, Julia C., *et al.* [125]	Torso	Squeeze
Affective Haptics	Compton, C., *et al.* [126]	Torso	Squeeze
Affective Haptics	Foo, E., *et al.* [162,163]	Torso, Arm, etc.	Squeeze
Affective Haptics	Yarosh, S., *et al.* [151,164]	Hand, Arm, etc.	Press
Notification Interfaces	George Chernyshov *et al.* [91]	Finger	Squeeze
Notification Interfaces	Liu, Q., *et al.* [64]	Arm	Stroke
Notification Interfaces	S. Ghodrat, *et al.* [92,165]	Arm	Stroke, Press
Notification Interfaces	Jones, L. A., *et al.* [62]	Torso	Press
Tele-operation	Kobayashi, F., *et al.* [166]	Finger	Drag
Interpersonal Communication	Suhonen, K., *et al.* [167]	Wrist	Squeeze
Toolkit	Messerschmidt, M. A., *et al.* [129]	Arm	Press, Pinch, etc.
Prototyping Platform	Muthukumarana, S., *et al.* [168]	Various Positions	Stretch, etc.
Not Defined	L Solazzi, M., *et al.* [169]	Fingertip	Stroke
Not Defined	Lücker M., *et al.* [170]	Hand	Stroke, Press
Not Defined	Knoop, E., *et al.* [128]	Wrist	Stroke
Not Defined	Gupta, A., *et al.* [171]	Wrist	Squeeze
Not Defined	Nakamura, M., *et al.* [88]	Torso	Press
Not Defined	Hamdan, N.A.-h., *et al.* [98]	Arm, Neck, etc.	Pinch, Press, etc.
Not Defined	Sun, R., *et al.* [96]	Arm, Leg, etc.	Pinch
Not Defined	Kim, J. H., *et al.* [97]	Hand, Ankle, etc.	Pinch, Twist, etc.

thermal properties, to express physical perception and interactions with virtual objects [140]. Current SMA-based haptic wearables for VR/AR focus on simulating the shape and weight of virtual objects. Most of the current SMA haptic devices in this category are designed for the fingers or the hand (see Table 3).

Fig. 7(a) is a diagram of a type of SMA-based VR haptic device system summarized from the literature [73,90]. The position changes of the virtual objects on the screen should be synchronized with users' movements. Data collected by sensors in the wearable device is continuously sent to the main computer through Bluetooth. Once the preset conditions are fulfilled, i.e., a user's hand reaches a target position, the main computer will send an actuation command, and the microcontroller activates the SMA subsequently.

Lim *et al.* developed a finger-wearable tactile interface *HaptiCube* with several SMA wires [94]. With different SMA wires actuated, the device displays five-degrees-of-freedom haptic feedback. *HaptiCube* is able to express pressure by the device increases in proportion to the falling beads (see Fig. 7(b)). Kim *et al.* designed VR gloves by using several SMA textile actuators, which were placed at the finger joints. With different actuation points, users can feel virtual objects in diverse shapes (see Fig. 7(c)) [89]. Similarly, "*Skin+*" made with SMA and auxetic structures was able to provide users with a simulated feeling of "catching something" [141]. "*Touch me gently*" can provide feedback which was close to real touch [93].

To obtain realistic haptic feedback, the force generated by the SMA actuators during interaction with virtual objects should be consistent with the force that users feel in real life. The actuation force of SMA increases with higher temperature, which means that to avoid excessive force, a method to regulate SMA's temperature should be used. The first option is to figure out the relationship between SMA actuation force and temperature by performing material tests, and then link the temperature to the applied current (refer to Rao's work in chapter 7 [45]). This option might involve modelling processes. With the models' help, the main computer can predict the SMA actuation force with the applied current values, and can cut off the power or lower the current when the force is too high. Some existing SMA constitutive models [142,143] and practical models [45,64] are valuable references for this method. The second option is to embed extra temperature or force sensors, to detect SMA's working status and collect data for further evaluation (e.g. *HaptiCube* [94]). Compared with the first option, the second one is relatively simple, but it might increase wearable devices' weight and volume.

In addition to force feedback, response time is another factor that affects users' haptic experience when using VR/AR wearables. For example, in Hwang's study, they found that when a user moved out of the surface of the virtual objects, SMA actuators still generated force feedback on users' fingertips [73]. It is because the cooling speed of the SMA is relatively slow. In VR/AR environments, excessive latency can lead to a decrease in immersion, inconsistency in motion, and may even result in symptoms such as motion sickness [144,145]. Therefore, it is necessary to reduce the cooling time with a current-modulation method or cooling mechanism (refer to section 2.2 (3)).

(2) Affective haptics

Affective haptics refers to the design of devices and systems that can detect, process, or display the emotional state of humans by means of the sense of touch [10]. *Social touch technology* and *mediated social touch* are similar concepts, which emphasize the employment of haptic

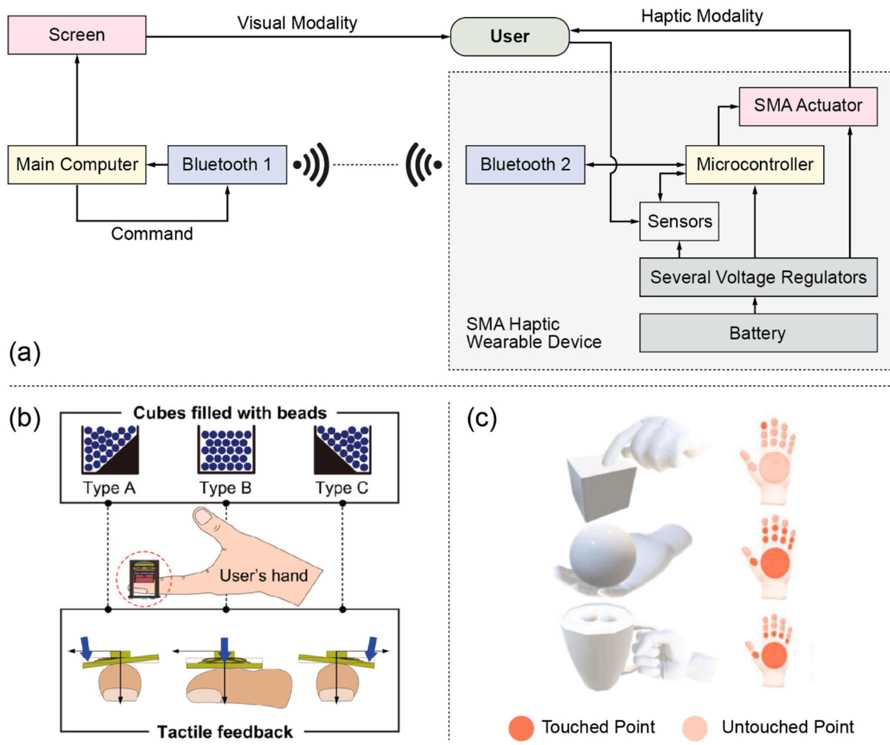


Fig. 7. (a) A brief diagram of a type of SMA-based VR haptic device system [73,90]. (b) *HaptiCube* has 5 degrees of freedom, and can simulate the weight of the falling beads [94]. (c) A VR glove with several SMA actuators at the finger joints (orange colours). With different actuation points, users can feel shapes of different objects [89].

technology for social interactions, including human communication via technology and interactions with responsive artificial social agents [146–148].

Most of the current SMA-based affective haptic devices focus on the squeeze-type haptic feedback (see Table 3). The sensation of squeezing in haptic devices is particularly suitable for simulating *deep touch pressure*, which is a type of tactile input received when firmly touching, holding, swaddling, or hugging [149]. Research shows that *deep touch pressure* can help reduce anxiety [150]. A relevant example is "*Hugging Vest*" (see Fig. 8(a)), enabling parents or occupational therapists to give remote warm "hugs" to children with mental illness [125]. Similarly, Kim also designed *SereniSleeve* for anxiety regulation (Fig. 8(b)) [82].

Yarosh *et al.* developed the *SqueezeBands* system, which augments social gestures over videochat with haptic actuation (see Fig. 8(c)) [151]. They demonstrated that *SqueezeBands* was appropriate for easing mental and physical demands in high-emotion tasks. Wang and Quek designed an upper arm squeeze-type SMA-based haptic device, and their research showed that remote touch can reinforce the meaning of a symbolic channel reducing sadness significantly [152].

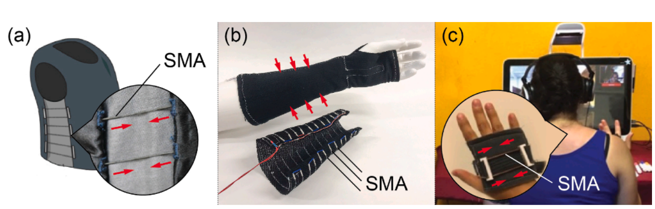


Fig. 8. (a) *Hugging Vest* can generate a squeeze sensation on users' trunk [125]. Red arrows indicate the actuation behaviours upon heating. (b) *SereniSleeve* for anxiety regulation [82]. (c) *SqueezeBands* for videochat [151].

(3) Notification interfaces

Notification interfaces can be defined as applications that facilitate the delivery of reminders, updates or alerts to the users [153]. The *SCWEES* (Fig. 4(b)), made by 3D printed semi-flexible structure and SMA wires, can generate displacement and force on the wrist's skin [127], which enables non-intrusive notifications. Some researchers have not explicitly defined the specific purposes of their devices; however, their prototypes also demonstrate the potential for use as notification interfaces. Examples include "*Tickler*" [154] (refers to Table 2(c2)), *Fingertip Tactile Glove* [155].

4.2. Summary of reported user studies

The focus of user studies largely depends on the application domains of haptic devices. Research on notification interfaces primarily emphasizes the evaluation of device performances. In contrast, studies in the realms of VR/AR and affective haptics tend to concentrate on users' emotional experiences (e.g. happiness, sadness and anger) while interacting with SMA wearable haptic devices.

Usability evaluation involves many parameters, such as force, displacement, and the actuation speed of the SMA system. As explained in section 3.1, these parameters can affect the noticeability and discriminability of devices and have a significant impact on usability. Some research has included relevant performance studies, such as "*SCWEES*" [60] and "*In contact*" [127], which investigated the strength of sensation perceived by participants. Effective devices should elicit positive emotional responses from users. Various methods are employed to assess users' feelings during device usage. Researchers can ask participants to rate their experiences, such as "*pleasantness*", "*displeasure*", "*comfort*" and "*immersion*" with *Likert Scale* [127,152], or request them to describe their experiences through questionnaires [141]. Wang and Quek employed *Pre- and Post-positive Affective Negative Affective Schedules* to measure the changes in users' feelings and emotions before and after they used the haptic device [160,172].

Note that in most cases, a user study is not the final step of the research. It usually accompanies the entire mid- and late-stage process of haptic device development, as the results of the user study can guide the design [173]. For example, in Kim's research, which is an SMA-based squeeze device (see Fig. 8(b)), several user studies were conducted [82]. At the early stage, different SMA mechanisms (including b1, b2 and b4 in Table 2) were developed to evaluate which can generate desired squeeze sensations, and then mechanisms b4 based on different SMA wire diameters were fabricated for another test. SMA with larger diameters can generate higher force, but would reduce the comfort of wearables as the prototype becomes stiffer. In the final user study, they investigated whether the haptic device could reach its design goal. Similarly, with the results of the user study, Hamdan *et al.* summarized the noticeability, discriminability, comfort and reaction time of *Springlet* (see Fig. 5(d)) on different body locations (e.g. wrist, arm, shoulder, neck, chest and back) [98], which is valuable information when deciding on where to attach SMA-based haptic devices to the body.

5. Discussion and outlook

Working performances and features of SMA technologies are clarified in section 2. Prior to selecting the SMA materials for wearable haptics design, it is recommended to conduct a thorough assessment and contrast with other emerging technologies (e.g. EAPs, MRFs). Generally, SMA actuators can produce different haptic feedback types as listed in Table 2. They are especially suitable for squeeze and stroke feedback types owing to their characteristic of shrinkage upon heating. As for EAPs, they are more applicable for haptic devices which can generate press feedback (e.g. fingertips devices [174]) due to their large deformation capacity. However, EAPs' actuation force is relatively low and they often require a much higher voltage to activate (from hundreds of volts to a few kilovolts). Most of the existing MRFs-based haptic wearable devices are gloves for VR [175,176], which can generate force feedback on users' fingers. Actually, MRFs have more applications in surgical instruments as they can give passive feedback by slowing down human-initiated movements [177]. For more details about these smart materials refer to the literature [22,24].

5.1. Design process for SMA-based wearable haptics

In the traditional product design process utilizing conventional materials, designers often explore various textures and finishes during the later stages of product development. Their primary considerations and choices emphasize aesthetic appeal. Compared with conventional materials, smart materials including SMAs serve as functional actuators in systems, influencing aesthetics as well. Thus, it is imperative to thoroughly assess material properties, performance, and associated factors during early design stages. Material-centered approaches are an option for developing smart materials-based devices, which emphasizes the importance of understanding and leveraging the unique attributes of materials in order to create innovative and functional products. As a type of material-centered approach, *Material Driven Design (MDD)* [178] has been used in research involving emerging materials [179]. The material-centered approach can also be applied to the development of SMA-based wearable haptic devices [92]. Nonetheless, this method primarily emphasizes materials and their properties, advocating for the exploration of potential applications. It may not be entirely appropriate for developing products with pre-identified specific requirements. For designers with definitive objectives for their haptic devices, the subsequent design process based on material-centered approach can serve as a reference.

(1) Selection of haptic feedback type

Five haptic feedback types that SMA actuators can provide are listed in Table 2. Designers can make selections according to application scenarios of their conceptual haptic devices.

(2) SMA materials tinkering

This hands-on, exploratory activity can assist designers in acquiring a preliminary understanding of SMAs' "shape memory" ability. Two experiments are recommended in this step. The first involves conducting a tensile test using a slender SMA wire measuring 50–100 cm in length. A counterweight can be attached to one end of the wire, causing it to stretch due to gravitational force. Subsequently, an electric current can be applied to heat the SMA wire, enabling it to counteract gravity and raise the counterweight. This tensile experiment demonstrates the high actuation force and small actuation displacement of SMA wires. The second test involves custom shape training of SMAs. Designers can create desired shapes by bending wires with a suggested diameter of over 0.5 mm. These custom shapes should be securely fixed using fixtures and then trained in a 500 ℃ oven. After cooling in cold water, the wires can deform at low temperatures but return to custom shapes when heated. This experiment exhibits the *shape memory effect* in the bending mode. For more information, refer to Rao's research [45].

(3) Reversible SMA mechanism design

Some SMA mechanisms are shown in Table 2, categorized by haptic feedback types. Designers may choose an appropriate mechanism or create new ones. A challenging step involves pairing SMAs with suitable bias force (e.g. coil spring, elastic band, another SMA wire), which must be sufficiently strong to deform SMAs in their cold state without impeding their return to original shapes at high temperatures. Sequential tests with various SMA wires and antagonists may be required to identify the optimal pairing.

(4) Comparing mechanism working performances with haptic perception parameters

Utilizing SMA mechanism actuators, fundamental performance metrics like actuation force and stroke can be assessed and compared to haptic perception parameters. For a haptic navigation device designed to generate stroke sensations on the skin, it is essential to ensure that the actuation displacement of SMA actuators exceeds the perception threshold required for tactile direction discrimination.

(5) Design and construction of wearable haptic devices

The concept of "wearability" in wearable technology encompasses factors influencing the wearer's comfort, including physical, psychological, and social aspects [180,181], all of which must be taken into account during the design process. Furthermore, wearable haptic devices require close skin contact to effectively deliver haptic feedback to users.

(6) User study of the devices

User studies aim to explore the user experience of haptic devices, enabling the collection of valuable feedback for subsequent iterative design improvements.

5.2. Future applications

(1) Designing with visually impaired people

There are approximately 285 million people with visual impairments in the world [182], and the number is expected to increase in the future. Auditory cues are a primary method of feedback in navigation and movement assistance tools, owing to the considerable capacity of the auditory sense to convey information [183]. Nonetheless, the sole reliance on the auditory modality for information conveyance may prove insufficient, and sound-based cues can inadvertently mask delicate auditory signals utilized by visually impaired individuals [184], especially in emergencies [185]. Therefore, haptic communication offers an alternative means of transmitting sensory information.

Visually impaired individuals necessitate adaptable haptic devices to cater to their varied requirements. Within the realm of education and learning, SMA technology has been employed in refreshable tactile displays [186–190]. However, their full potential has yet to be realized in the development of other diverse assistive equipment. For instance, educational activities that involve diagrams can pose challenges for those lacking visual image cognition, and collaboration between visually impaired individuals and sighted peers may prove difficult. Although some studies have tackled these issues [191,192], they have primarily focused on alternative haptic technologies. It is anticipated that the field will witness increased applications of SMAs in this domain.

In the navigation field, most existing haptic devices rely on vibration (e.g. *Travel Path Sounder* [193], *Miniguide* [184]). Given that roadway entities, such as vehicles and pedestrians, frequently exhibit dynamic and unforeseeable behaviors, vibration technology has an advantage owing to their response speed. However, it maybe not intuitive because users are required to learn the meanings of different vibration patterns [185]. SMA-based haptic devices can address this by swiping in various directions on the skin with the stroke haptic type, which is an instinctive method for indicating direction. They are suitable for circumstances that do not require frequent directional adjustments. Thin SMA wires or other alternative methods can be adopted to reduce the response time.

(2) Immersive technologies

Immersive technologies refer to technologies that blur the boundary between the physical and virtual worlds and enable users to experience a sense of immersion [194,195]. The market for immersive technologies, including augmented reality and virtual reality, has expanded to various industry domains, such as tele-manipulation, medical training, gaming and entertainment [22]. To emulate the perception of tactile sensations in a realistic manner, multiple points of interaction should be facilitated, but this would dramatically increase the complexity and bulkiness of the hardware [3]. SMAs are lightweight and have high power-to-weight ratios. It makes them an appropriate option for developing wearable haptic devices in the field of virtual reality where limiting the size and weight may be crucial for supporting satisfying user experiences.

In contemporary VR electronics, the harmonization of various output modalities, including visual, auditory, and haptic, can effectively enhance users' immersive experiences. Nevertheless, the majority of present research on SMA haptic devices primarily investigates the impact of diverse haptic feedback types on users' perceptions, without integrating visual and auditory elements. It implies that the potential of SMA technologies has yet to be thoroughly explored and harnessed.

(3) Remote interpersonal haptic communication

Tactile signals constitute a vital component of daily affective communication. Research shows that mediated touch can help reduce stress and build social connections between users [146,148,196]. Individuals engage in various forms of physical contact, such as handshaking during greetings, seeking hugs for emotional support when feeling low, and clapping to express excitement. These tactile interactions serve as essential components of interpersonal communication, helping to establish social connections, convey emotions, and strengthen bonds between individuals.

Replicating the feel of authentic human touch contact is a formidable challenge, and current technology lacks the sophistication to mimic all the qualities of real touch [197]. Vibrotactile actuators are small, inexpensive and easy to control [198]. Nevertheless, research indicates that force feedback actuators are perceived as more natural compared to vibrotactile touch, leading to increased emotional interdependence [199]. Jewitt *et al.* presented that to bring the richness of "real" touch into the digital, there is a need to "move beyond vibration" [200]. A survey conducted during the COVID-19 lockdown revealed that over 90% of participants expressed missing hugs, while approximately 20% missed receiving a stroke or a pat on the shoulder [201], which is challenging to replicate with existing commercial haptic technologies. As depicted in Table 2, SMAs are able to generate various haptic types with different mechanism designs. By integrating various haptic modalities, such as thermal feedback, SMA-based haptic devices have the potential to generate more natural and realistic feedback. Moreover, In a longitudinal study examining the use of squeeze bracelets for couples, researchers discovered that the sound produced by the bracelets was occasionally perceived as annoying [202]. This observation could highlight another benefit of SMA technology, which is noiseless during actuation.

6. Summary

In recent decades, the haptics field has experienced significant advancements, and the demand for advanced haptic technologies continues to grow. Despite this, only a few technologies have reached commercial success. One challenge in developing innovative haptic devices lies in balancing their size and the variety of haptic experiences they offer. Generally, haptic devices capable of offering sophisticated and natural tactile feedback tend to contain numerous mechanical components, resulting in bulkiness and difficulty to wear. Shape memory alloys (SMAs) are lightweight, compact, and possess high power-to-weight ratios. Additionally, they can be integrated with textiles, offering considerable aesthetic appeal. These attributes make SMAs suitable for designing wearable haptic devices, although certain limitations, such as long actuation time and low energy efficiency, might constrain their application scope.

This review offers a concise introduction of SMA working principles, performances, and features, complemented by an analysis of existing SMA-based wearable haptic devices found in the literature. The correlations between haptic and SMA material fields are elucidated. Haptic perception information can be valuable for designing SMA actuators, while distinct SMA actuator mechanisms can offer a variety of haptic types. Application domains of existing devices are categorized, and user studies of the devices are summarized. A recommended design process for SMA-based wearable devices is proposed in the discussion. Given the characteristics of SMAs, we believe they hold potential for designing haptic devices for visually impaired individuals and demonstrate significant promise in the areas of immersive technologies and remote interpersonal haptic communication.

CRediT authorship contribution statement

Qiang Liu: Investigation, Writing – original draft, Writing – review & editing. **Sepideh Ghodrat:** Supervision, Writing – review & editing. **Gijs Huisman:** Writing – review & editing. **Kaspar M.B. Jansen:** Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data are presented and summarized in the paper.

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