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REVIEW

4D printing of soft orthoses for tremor suppression

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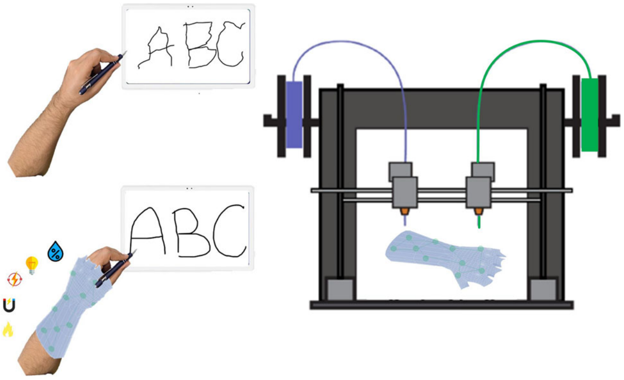
Abstract

Tremor is an involuntary and oscillatory movement disorder that makes daily activities difficult for affected patients. Hand tremor-suppression orthoses are noninvasive, wearable devices designed to mitigate tremors. Various studies have shown that these devices are effective, economical, and safe; however, they have drawbacks such as large weight, awkward shape, and rigid parts. This study investigates different types of tremor-suppression orthoses and discusses their efficiency, mechanism, benefits, and disadvantages. First, various orthoses (with passive, semi-active, and active mechanisms) are described in detail. Next, we look at how additive manufacturing (AM) has progressed recently in making sensors and actuators for application in tremor orthoses. Then, the materials used in AM are further analyzed. It is found that traditional manufacturing problems can be solved with the help of AM techniques, like making orthoses that are affordable, lighter, and more customizable. Another concept being discussed is using smart materials and AM methods, such as four-dimensional (4D) printing, to make orthoses that are more comfortable and efficient.

Graphic abstract



Keywords Tremor suppression · Parkinson's disease · Essential tremor · Additive manufacturing · 4D printing

Introduction

Tremor is an involuntary quivering movement of a body part, which is usually rhythmic and oscillatory [1]. This involuntary movement interferes with affected patients' activities of daily living (ADL), such as drinking, eating, writing, dressing, or bathing. Tremors are the most common type of movement disorders and are either associated with other neurological conditions such as Parkinson's disease (PD) and essential tremor (ET), or are a result of drug or alcohol abuse [2]. Among diseases with tremor symptoms, PD and ET prin-

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cipally affect the upper limbs and make ADLs harder for patients.

Since the causes of PD and ET are uncertain [3], their treatment options focus on symptomatic relief [4]. While drugs are the most frequent form of treatment for tremors, up to 53% of the patients stop using them because of the lack of effectiveness or adverse effects [5]. Deep brain stimulation is a surgical procedure to relieve PD and ET symptoms. However, it is an invasive treatment that can lead to side effects such as changes in the behavioral, cognitive, and mental status in up to 48% of the individuals undergoing surgery [6]. Therefore, patients who do not respond to medicine or are ineligible for deep brain stimulation require alternative treatments. Noninvasive treatments such as occupational therapies, handheld devices, and wearable devices can act as substitutes for medications and deep brain stimulation. As occupational therapies usually provide a short-term treatment option and handheld devices are designed for specific tasks, at present, wearable devices are the only viable alternatives for patients to attenuate their hand tremors and regain their ability to perform daily tasks.

Tremors exhibit varying characteristics according to the underlying disease. Researchers have classified tremors based on their features as follows:

1. Tremor situation: Based on the tremor phenomenology, the tremor can occur in the resting, postural, or active positions [7]. A rest tremor occurs when a limb does not have voluntary movement and is supported against gravity. On the other hand, if a tremor occurs during muscle contraction, it is called an action tremor. Action tremors have certain subclassifications, as described in Table 1.
2. Tremor joint: PD and ET tremors mostly appear in the upper limb joints and muscles. As shown in Fig. 1, the mechanical model of the upper limb (including the shoulder, elbow, and wrist) has a total of seven degrees of freedom (DOF).
3. Tremor severity: Tremor severity is classified into three groups: mild, moderate, and severe. It is possible to measure tremors with electromyography or accelerometers, and they can be classified based on their signal characteristics, such as amplitude and frequency [8].

PD tremors are usually resting tremors that disappear when the patient starts to use their hand. Their frequency ranges from 3 to 5 Hz [1]. Furthermore, postural tremors occur in about 90% of PD patients with resting tremors [9], and they have similar frequencies. ET is the most common movement disorder of the upper limb [10], which usually occurs in kinetic situations, commonly in the arm and hand muscles [11], featuring a larger amplitude than PD's postural tremors [12]. ET tremors are known as mid- to high-frequency tremors, and range from 5 to 10 Hz [1]. In a study of 11 PD and 10 ET cases, the postural tremor amplitude in PD cases was reported to be 2.7 times larger than that in ET cases on average [13]. Different studies on ET have shown that forearm rotation and wrist flexion/extension tremors are the most severe kinetic tremors [14]. Different DOFs have almost the same distribution order as posture tremors, except for the forearm rotation tremor that has smaller power than wrist flexion/extension [15].

Table 1 Phenomenology of tremors [7]

Tremor type	Definition
I. Rest	Occurs when voluntary muscle activity is absent and the limb is supported against gravity
II. Action	Occurs with voluntary movement or sustained posture caused by muscle contractions
a. Postural	Occurs when stretching and holding limbs motionless against the force of gravity
Reemergent	A particular type of postural tremor that commences after several seconds
b. Kinetic	Occurs with voluntary motion
c. Intention	Occurs with goal-directed movement and worsens when approaching the target

The remainder of this paper is structured as follows: in "Tremor suppression mechanisms" section, the existing pharmacological, surgical, and therapeutic treatments of tremors are reviewed, followed by a summary of handheld devices for tremor suppression. Then, various types of tremor suppressors, including passive, semi-active, and active mechanisms, are presented. In "Additive manufacturing of soft orthoses and materials" section, additive manufacturing (AM) methods and materials for fabricating multiple sensors and actuators (used in tremor-suppression orthoses) are discussed. The current challenges and future directions for tremor-suppression orthoses are given in "Discussion" section. Finally, the paper is summarized and concluded in "Conclusions" section.

Tremor suppression mechanisms

Medical treatments

Pharmacological approach

Over the past few decades, researchers in various fields have attempted to find methods to stop tremors caused by PD or ET, including pharmacological, surgical, and therapeutic strategies, which are summarized in Table 2. Pharmacological treatments for ET have been the first and most well-known choice for patients since the 1970s. Propranolol as a beta-blocker drug is one of the most common drugs for ET, while it has side effects such as headaches and insomnia, which

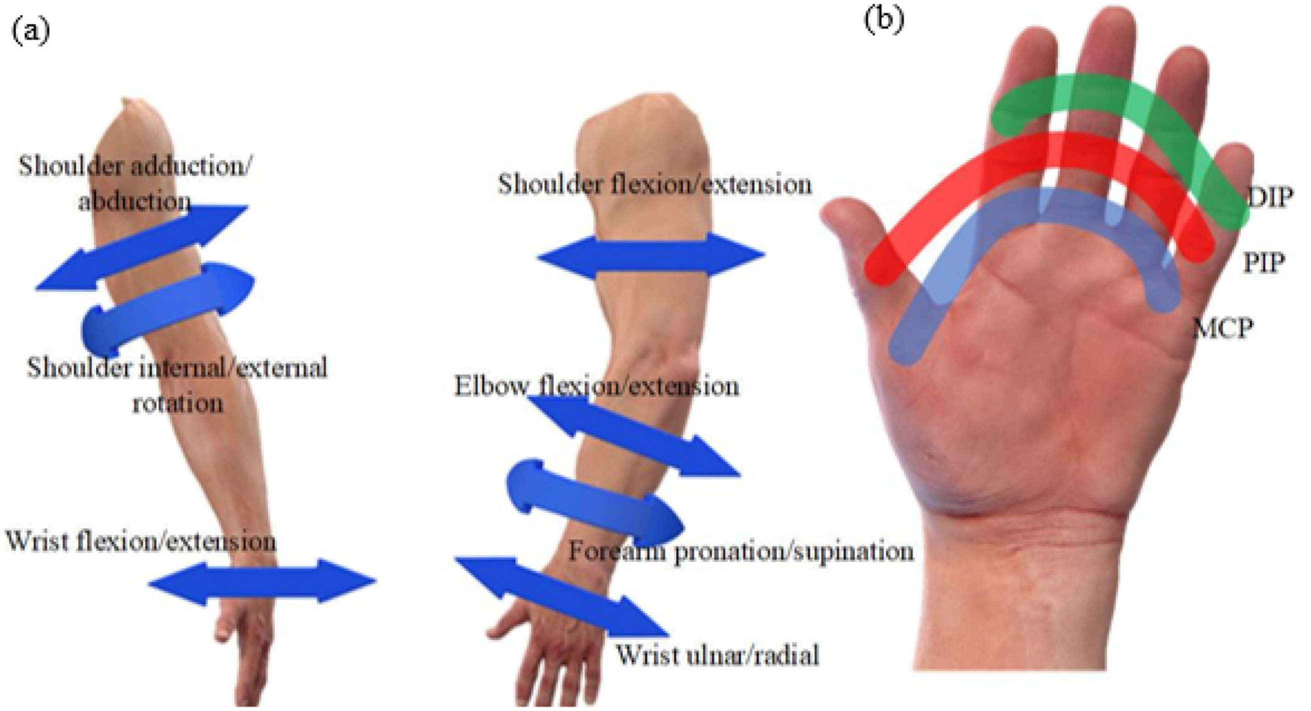

Fig. 1 **a** Arm degrees of freedom (DOF); **b** finger joints, including the metacarpophalangeal (MCP) joints, proximal interphalangeal (PIP) joint, and distal interphalangeal (DIP) joint

could lead to contraindications with other drugs used by the patient [16]. Furthermore, some patients do not respond to this type of drug [16]. Another recommended medication for suppressing tremors in the limbs is primidone. A study on 11 patients showed that the efficacy of primidone decreases over time (from 45% in the first month to 41% in the twelfth month) [17]. Almost half of the individuals with ET who take this medication exhibited recurrent tremors or insufficient improvement in tremors, intense adverse effects, or contraindications to the medicine [18]. Another study revealed that propranolol and primidone can cost about $269 annually (assuming that people take both medications) [19]. Dopamine-based drugs such as levodopa, dopamine agonists, or monoamine oxidase-B have been prescribed for PD patients, although side effects like nausea and dizziness have been reported [20]. A 48-month study to compare levodopa and dopamine agonists reported that, even though levodopa has more severe side effects, it has a 3.4 ± 12.3 improvement score compared to the Unified Parkinson Disease Rating Scale (UPDRS) score (a rating tool, with scores from 0 to 199, used to evaluate the severity of PD), when evaluated in the first month [21]. At the same time, dopamine agonists decrease the UPDRS score by 1.3 ± 13.3. Research in the UK has shown that the cost associated with levodopa/carbidopa intestinal gel (a combination of levodopa and carbidopa in a ratio of 4:1) treatment is about $130,000 in a lifetime [21].

Table 2 Surgical, pharmacological, and therapeutic treatments for upper limb tremor

Treatments	Adverse effects
Pharmacological	
Propranolol	Headaches and insomnia, contraindications with other drugs; some patients are unresponsive to propranolol
Primidone	Nausea, dizziness
Surgical	
DBS	Dysarthria, disequilibrium; efficacy can decrease over time
MRIgFUS	Transient: sculpt burn and numbness, head pain, nausea Persistent: paresthesia and ataxia
Therapeutic	
Weighted therapy	Muscle fatigue, some studies show no efficiency
Cooling therapy	Temporary effect; effective for some daily tasks
Vibration therapy	Some research reports no efficacy

Surgical approach

Another solution to cope with diseases that have tremor symptoms is surgical intervention. Thalamic lesioning was the first described surgical solution for ET. Deep brain stimulation (DBS) was performed in the 1990s by surgeons to treat ET and PD. During DBS surgery, electrodes are precisely implanted in the subthalamic nucleus and connected to a pulse generator. Then, the pulse generator is programmed to stimulate the brain to decrease tremors and other symptoms of the disease. In a study involving 28 ET patients, the efficacy of the surgery decreased from 66% improvement in year one to 48% after 10 years [22]. Dysarthria and disequilibrium have also been reported as side effects of DBS surgery [23]. In addition, DBS surgery is not cost-effective at $37,000 for primary surgery [19]. A less invasive treatment for these conditions is magnetic resonance imaging guided focused ultrasound (MRIgFUS), which does not need surgery because the ultrasound waves can penetrate and burn the thalamus directly. Even though significant improvements in tremor have been reported in ET and PD patients after MRIgFUS treatment, it has transient adverse effects such as sculpting burn and numbness, headache, nausea, along with persistent side effects like paresthesia (a burning or prickling sensation) and ataxia (disorders that affect coordination, balance, and speech) [24, 25]. MRIgFUS can also cause unintended damage to other nerves, leading to muscle weakness or a loss of sensation (this effect can be transient or persistent). Furthermore, this treatment is unavailable for the majority of patients because it costs nearly $20,000 [19], and there is a 9% chance of tremor recurrence in the first year [26].

Table 3 Different types of wearable hand tremor suppressors

Electrical	Uses an electrical signal to stimulate muscle
Mechanical and electromechanical	
Passive	Uses mechanical force to suppress tremors, but can affect voluntary motion
Semi-active	Uses mechanical force to absorb tremors and can affect voluntary motion, but is tunable to a different frequency (in some cases, it can be turned on or off depending on tremor occurrence)
Active	Uses mechanical force to mitigate tremors Uses mechanical force to support voluntary motion

Therapeutic approach

Therapists have suggested different techniques to alleviate the effects of tremors on patients' lives. Although weighted therapy does not result in hand tremor improvement [27], it is one of the most common therapeutic treatments for tremor. Another therapeutic treatment is called "cooling therapy." Researchers reported that cooling therapy could significantly decrease tremors in ET patients who were drawing spirals or feeding [28]. In a study involving 18 patients, individuals tracked computer mouse cursors to a target point on a monitor before and after limb cooling [29]. The results showed that patients had a 15.6 mm average endpoint error, which dropped to 9 mm 30 min after cooling. However, cooling or warming the limb had no effect on tremors in the upper limb [28]. In addition, vibration therapy has been tested on ET and PD patients, and devices like the Vilim ball (various frequencies from 8 to 18 Hz and 0–2 mm amplitude) work based on vibration therapy [30]. It was further indicated that mechanical vibration with a frequency between 50 and 450 Hz could not reduce hand tremors for ET [31].

Handheld devices

Handheld devices were developed as an additional strategy to cope with tremors in ET and PD patients. Engineers and researchers around the world have made utensils, writing tools, clothing designs, computer and phone accessories, and applications to make life easier for patients with upper limb tremors. Spoons with active cancellation of tremors (ACT), such as Liftware Steady, can reduce the tremor of the utensil by around 71 to 76% [32], although their battery life and price can be a deterrent to their wide application. Research on 16 PD patients with three different spoons and weighted bracelets showed that weighted utensils alone could not improve hand tremors with regard to their amplitude and frequency [27].

Wearable devices (exoskeleton)

A practical approach to improving hand tremors is to use wearable devices or exoskeletons. Tremor exoskeletons could be mechanical, electrical, or electromechanical. Electrical devices or functional electrical stimulation (FES) devices generate electrical signals and cause muscle contractions through electrodes [33]. Reports showed good efficiency for FES devices, but patients could feel numbness or a burning sensation in their arms [34]. Moreover, pregnant and cancer patients, along with those that have implanted electrical devices in their bodies, cannot use FES [35]. Wearable tremor suppressors also include mechanical and electromechanical types, which can be classified as passive, semi-active, or active, based on their mechanisms. Passive devices can suppress tremors, but they also affect voluntary motion. On the other hand, active devices can suppress tremors and support voluntary muscle contractions at the same time. Furthermore, they are usually adaptive to tremor frequency and amplitude, and can be switched on or off based on the presence of the tremor. Semi-active devices

Table 4 Passive mechanisms for upper limb tremor suppression

Year	Mechanism	Advantages/disadvantages	Type of tremor	Performance
1998 [36]	Friction	Light, simple/damp intentional force	Wrist flexion/extension	NR
2004 [37]	MSD	Tunable/low efficiency	Shoulder and elbow flexion/extension	~96% (14.27 dB)—tested on mechanical hand
2018 [38]	MSD	Compact/limits hand motion	Elbow flexion/extension	80%—results from Simulink, mechanical model, and patients
2018 [39]	MSD	High efficiency/heavy, bulky	Forearm pronation/supination	85%—tested on a mechanical model
2018 [40]	Magnetic damper	Lightweight/bulky	–	NR
2020 [41]	Air bag damper	Lightweight, tunable/suppresses voluntary forces	Wrist flexion/extension	Up to 84%—tested a PD subject
2017 [42, 43]	Non-Newtonian	Compact/rigid actuator	Wrist flexion/extension	0.57-point score clinical
2011 [44]	Air dashpot	Lightweight/damps voluntary motion	Wrist and elbow flexion/extension and wrist ulnar/radial	82% on elbow tremor
2020 [45]	Particle damper	Simple/low efficiency	–	Up to 37%
2019 [46]	Gyroscope	Tunable/limited to rest tremor, bulky, needs an energy source	Forearm pronation/supination	>50%—results from a mechanical model

act like passive devices in suppressing tremors; that is, they do not support voluntary motion while mitigating tremors, but can automatically tune to tremor frequency (Table 3).

Passive mechanisms

A mechanical orthosis is a kind of device that contains only mechanical parts, and it mitigates tremors without requiring an energy source or electrical units. Researchers have used different passive methods and devices (Table 4) to decrease tremor amplitude, starting with viscous beam wearable tremor suppression [36].

This kind of device is designed and installed on the dorsal side of the hand and forearm, and it decreases the wrist flexion/extension tremor amplitude based on friction; however, friction can also affect voluntary motion [36]. Another purely mechanical method to cope with tremors is a mass–spring—damper system (MSD). The MSD contains a mass and a spring; when its natural frequency is equal to the excitation frequency, vibrations are dampened [47]. In 2004, Hashemi et al. fabricated a tuned vibration absorber (TVA) based on the MSD mechanism to mitigate PD hand tremors [37]. Experiments on a mechanical hand with 2.7 Hz of tremor frequency showed 14.27 dB and 13.93 dB decreases in the upper arm and forearm tremor amplitude, respectively [37].

In 2018, Rudraraju and Nguyan designed a wearable passive tremor reduction device (TRD) to suppress hand tremors [38]. The results from simulation, mechanical hands, and patient tests showed a significant percentage reduction of 70% to 80% in tremor amplitude. The developed MSD unit weighs approximately 215 g, and the TRD device weighs about one pound [38]. In another study published in 2018, Buki et al. developed a passive hand tremor attenuation device called the Vib-bracelet, tuned to tremor frequency based on MSD (Fig. 2b) [39], to suppress pronation/supination tremors. This device includes an inner and an outer (57 mm radius) ring and weighs 280 g. The result of simulation and the manufactured prototype mounted on a mechanical model of the forearm showed a maximum of 85% mitigation of tremors at 4.75 Hz. However, the Vib-bracelet is heavy and bulky, and has not been tested on humans.

The magnetic spring mechanism is another passive method to reduce tremor amplitude. In 2018, Masoumi designed and manufactured a hand tremor attenuator glove based on magnetic forces (Fig. 2a) [40]. Hand tremor was simulated by fixing a vibrating motor on the human forearm. The tremor attenuator showed good efficiency in drinking and eating tasks, but not in attenuating tremor amplitude [40]. In 2020, Formme et al. proposed and implemented a new adjustable air-filled tremor attenuation orthosis (Fig. 2c) [41]. This device has a simple structure (an airbag) that can be adjusted by inflation or deflation. The orthosis was tested on a PD patient, and it showed good efficacy (74 to 84%) for drinking, pouring, and spiral drawing [41]. The device is attached to the dorsal side of the wrist and has a small effect on voluntary motion. Even though the device is lightweight (33 g) and compact, and does not require an energy source, it has to be inflated or deflated for different tasks to ensure that it has a task-specific size and stiffness to reach maximum efficiency. As upper limb tremor has a higher frequency than intended motions, non-Newtonian fluids are a suitable smart material to attenuate hand tremor. For example, Steadiwear

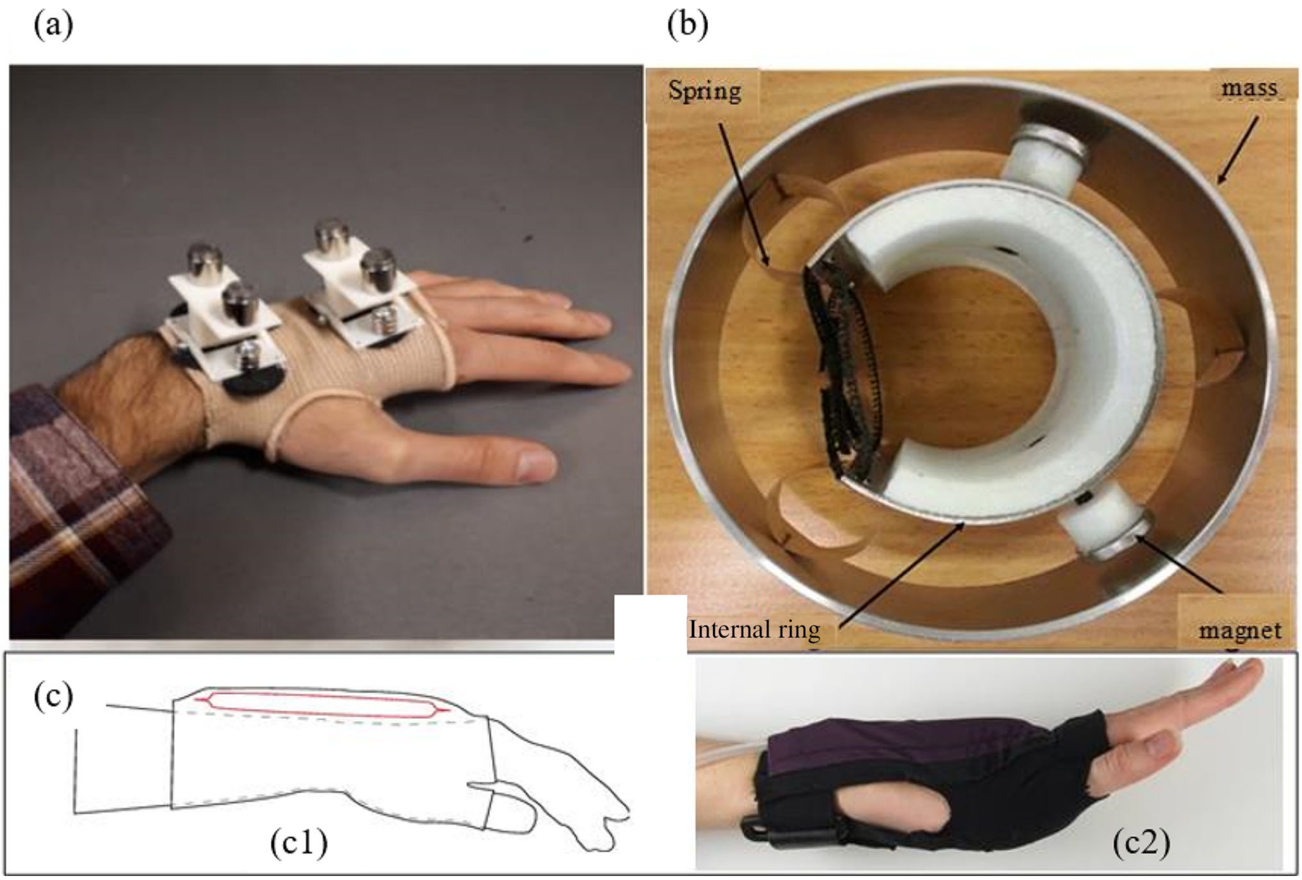

Fig. 2 Various passive mechanisms: **a** magnetic tremor suppressor (reproduced from [40], with permission from University of British Columbia under CC BY-NC-ND 4.0 license); **b** Vib-bracelet, designed to suppress forearm pronation/supination (reproduced from [39], Copyright 2017, with permission from International Federation for Medical and Biological Engineering); **c** Air-filled tremor attenuation orthosis—(c1) schematic view and (c2) fabricated glove (reproduced from [41], Copyright 2020, with permission from the authors, licensed under CC BY 4.0)

is a tremor damping glove that works with a non-Newtonian fluid effect [42, 43].

Takanokura et al. proposed air dashpots to mitigate tremors and implemented orthoses to suppress wrist and elbow flexion/extension and wrist ulnar/radial tremor. The device was tested on a healthy person with a muscle stimulator to generate tremors in the upper arm. The results indicated 62 and 82% tremor improvement in the wrist and elbow, respectively, when utilizing two dashpots [44]. In 2020, Lu and Huang proposed a particle damper to suppress tremors [45]. They confirmed the efficiency of the particle damping mechanism through numerical simulation and experiments. Furthermore, it was reported that the device performance improves by increasing the particle mass. Experiments proved that particle dampers have higher efficiencies at higher frequencies (up to 37%) [45]. In addition, the gyroscope effect has been used to suppress vibration in many fields. In 2019, Zulkefli et al. proposed an intelligent glove to mitigate resting hand tremor in PD by using the gyroscope effect [46]. They tested the glove on a mechanical model imitating resting tremors from 3 to 7 Hz, and the results exhibited a minimum of 50% reduction in tremor acceleration [46].

Semi-active mechanisms

In the semi-active approach of tremor suppression, engineers have tried to eliminate hand tremor and minimize the orthosis effect on voluntary hand motion. In such cases, most researchers applied passive methods to hand tremors with added controllers and sensors (Table 5). In 2013, Herrnstadt and Menon fabricated a friction-based tremor absorber device based on an electromagnetic brake system and designed to be fixed on the elbow (Fig. 3a) [48]. The prototype was 3D-printed and weighed 942 g. It contains magnetic brakes and two sensors to collect the tremor size and elbow angle. When a tremor occurs, the controller activates the brakes to decrease tremor amplitude. The tested results showed an 88% efficiency [48].

Table 5 Semi-active mechanisms for upper limb tremor suppression

Year	Mechanism	Advantages/disadvantages	Type of tremor	Performance
2013 [48]	Magnetic brake (friction)	Portable, lower power consumption/heavy, bulky	Elbow flexion/extension	88% on healthy volunteers
2005 [49]	MR	Low power consumption/suppresses intentional movement (17 dB)	Hand flexion/extension	43 dB
2021 [50]	MR + cylinder damper	Low power consumption/limits hand motion	Hand flexion/extension and ulnar/radial and pronation/supination	61.39%—tested on five healthy volunteers
2013 [51]	Self-tunable DVA	Simple mechanism/heavy and bulky	–	80%—simulated in MATLAB and tested on PD tremor signal
2020 [52]	SJS	High stiffness to mass ratio/limits hand motion	Hand flexion/extension	41%—tested on nine subjects
2020 [53]	LJS	Lightweight and easy to wear/limits hand motion	Finger flexion/extension	78.3%—tested on a mechanical hand model

Another method to utilize friction in tremor mitigation is to use magnetorheological (MR) fluid that contains distributed magnetic particles in a carrier fluid; when a magnetic field is applied to it, the fluid viscosity increases. MR fluid has good flexibility, high response speed, and variable impedance for use in tremor-suppression orthoses. In 2005, Loureiro et al. designed the double viscous beam device grounded on an MR fluid [49]. The results on an ET subject showed 43 dB and 17 dB decreases in tremor at 4 Hz and 1 Hz, respectively, along with low power consumption (1 W) [49]. Recently, Zahedi et al. designed and fabricated a controllable flexible semi-active actuator with MR fluid [50]. They added a cylinder–piston damper to increase the efficiency. Their test results on five healthy subjects showed 61.39 and 56.22% decrease in tremor acceleration and angular velocity, respectively [50]. Figure 3b shows an orthosis based on changing the stiffness of the MR fluid in a flexible link.

The natural frequency of a dynamic vibration absorber (DVA) can be changed by varying its mass or spring constant. Teixeira et al. presented a self-tunable DVA [51] and tried to tune the DVA frequency by changing its mass. The proposed system used two hydraulic pumps to fill or empty the DVA reservoir at a controlled rate to change its natural frequency. The proposed systems showed 50 and 80% efficiency, respectively [51].

There have been numerous attempts to exploit soft robots and smart materials for soft wearable orthoses. In 2020, Narang et al. developed a sandwich jamming structure (SJS) with a high stiffness range and stiffness to mass ratio [52]. The structure includes multiple layers (e.g., paper and textile) in an airtight bag. The layers are free to slide in the normal state, and the subject can bend the structure with slight resistance; however, if the controller vacuums the bag, the layer's friction increases and it becomes resistant to sliding. Based on this SJS characteristic, they proposed a soft wearable orthosis to mitigate upper limb tremor. The device prototype was tried on nine subjects and showed a 41% decrease in tremors in the ON-state, while it had a negligible effect on voluntary motion in the OFF-state [52]. Another study conducted by Awantha and colleagues in 2020 utilized a layer jamming structure (LJS) in suppressing hand tremor [53]. They attempted to eliminate finger tremor by fastening layer jamming and applying resistance to finger motion. To test the soft glove, a mechanical hand model was fabricated with the ability to imitate hand tremors between 3 and 6 Hz. The results showed a maximum of 78.3% decrease in tremor amplitude when the LJS was placed on the palm side, and a 38.2% improvement was reported on the dorsal side [53].

Active mechanisms

The weight of orthoses and braces can limit voluntary movement. Therefore, researchers have worked on another paradigm, called active attenuators, to mitigate this drawback for patients, developing and fabricating various devices (Table 6). In this approach, hand orthoses support voluntary motion and suppress hand tremors. In 2005, a wearable orthosis for tremor assessment and suppression (WOTAS) exoskeleton was manufactured [54]. This apparatus includes various parts, including direct current (DC) motors, sensors, and controller units. The DC motor power is utilized to suppress tremors in different joints, including wrist flexion/extension, forearm pronation/supination, and elbow flexion/extension. In a study on 10 patients with various tremor diseases, this type of orthosis was 40% effective [55]. Despite its efficacy, the WOTAS is too bulky and heavy.

In 2017, Zhou et al. proposed a multi-channel mechatronic splitter (MMS) to mitigate hand tremors while allowing patients to continue ADL without restriction (Fig. 4c) [56]. The MMS system is powered by a 2 W DC motor and weighs

Table 6 Active mechanisms for upper limb tremor suppression

Year	Mechanism	Advantages/disadvantages	Type of tremor	Performance
2005 [54]	DC motors	Supports intentional movements/bulky and heavy	Wrist and elbow flexion/extension and forearm pronation/supination	40% in 10 subjects with different diseases
2017 [56]	MMS + DC Motors	Multi-output MMS with just one DC motor/errors in voluntary motion tracking, bulky	Wrist and finger flexion/extension	NR
2019 [57]	Brushless DC motor and PID controller	3D-printed, high performance/bulky and heavy	Elbow flexion/extension	94% in nine patients with PD and ET
2020 [58]	Piezoelectric sensor and actuator	Combined actuator-sensor system/low displacement of the piezoelectric actuator under high voltage	Elbow and wrist joints	NR
2019 [59]	PMLM	Precise and less energy-consuming/rigid actuator, heavy	Wrist flexion/extension and ulnar/radial	30.51 dB effective in a mechanical model driven by PD tremor signals
2020 [60]	Fiber-reinforcement BPAM	Soft actuator/heavy (including pump)	Fingers flexion/extension	NR
2021 [61]	PAM	Soft actuator/heavy (including pump)	Wrist and fingers flexion/extension	70% in index finger tremor

129 g (excluding the motor and power supply). Data recorded from seven PD patients were used to evaluate the MMS, and the results showed a 12.4% root mean square error (RMSE) for voluntary motion tracking [56]. Recently, Herrnstadt and Menon designed and produced an active tremor suppressor orthosis (TSO) with brushless DC motors, proportional–integral–derivative (PID) controllers, proportional–integral (PI) controllers, and sensors to detect hand motion (Fig. 4a) [57]. This orthosis was designed to be fixed on the upper arm and forearm, weighing 1700 g. The device was tested on nine patients, including those with Parkinson's disease and essential tremors. The results showed a 94% reduction in the mean power of the tremor signal, and even though they nearly eliminated the interference of TSO on motion power and velocity, a small error in the position tracking of hand motion was reported [57]. Similar to WOTAS, this orthosis is also relatively bulky.

In 2019, Hosseini et al. designed a hand suppressor (active) with piezoelectric actuators and sensors on the top and bottom side of the arm [58]. The tremor data were collected through the piezoelectric layer, analyzed, and then mitigated using a proportional–derivative (PD) controller [58]. It was also reported that increasing the controller gain and piezoelectric constant can improve the efficiency of the attenuator. Furthermore, it has been shown that changing the dielectric constant does not affect the attenuator [62]. Zamanian et al. designed an active tremor suppressor (for extension/flexion and radial/ulnar tremors) through the use of permanent-magnet linear motors (PMLMs) and a notch filter (Fig. 4b) [59]. To evaluate the device, they employed a hand emulator running on recorded tremor signals from PD patients; a wavelet transform was used to analyze tremor signals with and without a tremor suppressor. They reported 30.51 dB and 13.89 dB suppression in the first and second components of the tremor signal, respectively, and claimed that it has a negligible effect on voluntary motion (0.36 N) [59]. The results showed that PMLM actuators are more energy-efficient than servo-pneumatic actuators.

In 2020, Wirekoh et al. proposed a hand tremor attenuator with fiber-reinforced bending pneumatic artificial muscle (BPAM) and fabricated it in a finger-scale size [60]. The prototype has good flexibility to move in a 40-degree peak-to-peak range at frequencies between 4 and 8 Hz (normal frequency for PD and essential tremor) [60]. In 2021, Skaramagkas et al. constructed another hand tremor suppressor orthosis (Fig. 4d) using PAMs [61]. The prototypes were manufactured to suppress different tremors of the wrist and finger extension/flexion. The orthosis contains accelerometer sensors to gather tremor data and a PID controller. In an experiment on an ET subject at different positions (postural and kinetic tremor), the results showed an efficiency of 70% for index finger tremor. Moreover, the orthosis reduced thumb and wrist tremor by 50 and 40%, respectively [61].

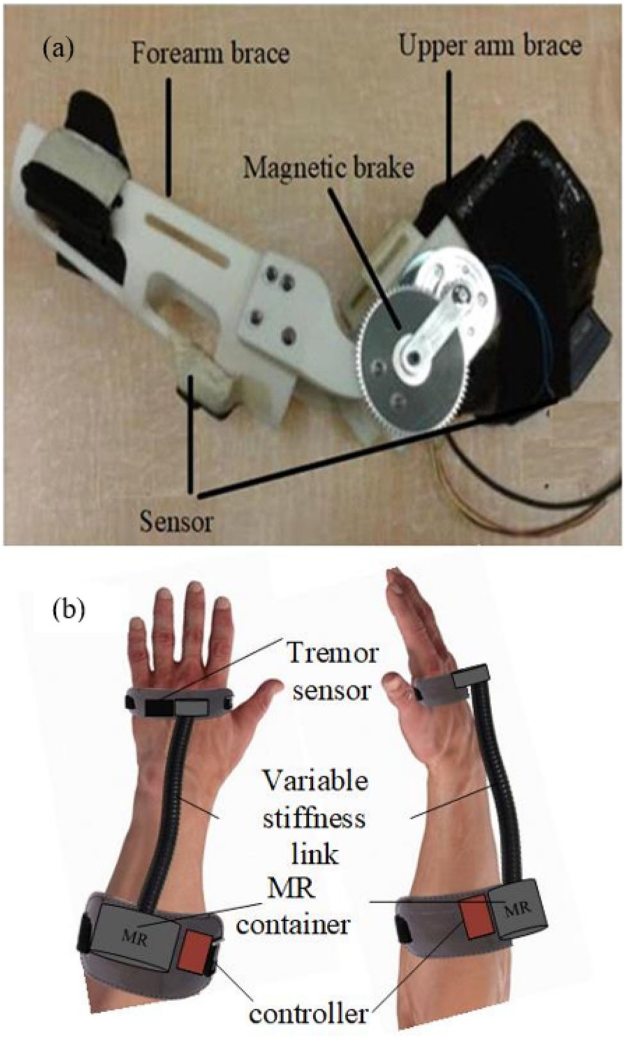

Fig. 3 Different semi-active mechanisms: **a** Magnetic brake tremor damper (reproduced from [48], Copyright 2013, with permission from the authors, licensed under CC BY 3.0); **b** flexible semi-active actuator based on MR fluid

Comparing passive, semi-active, and active mechanisms

In contrast to semi-active and active orthoses, passive orthoses do not have any components that require a power source. However, their simple mechanism for reducing tremors makes it difficult for people to move voluntarily. Furthermore, MSD-based passive devices incorporate components with additional mass, which makes them unwieldy for patients. For the semi-active method, researchers have often relied on the same method used in passive mechanisms. However, they add sensors and controllers to obtain feedback on tremors and tune the device automatically. Using traditional brakes or actuators makes these devices heavy and uncomfortable to the wearer. Active devices have high efficiency and can support voluntary movement, but their drawback is that traditional actuators require the fabrication of cumbersome and heavy orthoses. A major research direction is to reduce the total weight of the devices to increase their wearability. Recently, the proposal of smart materials [50] and soft actuators [52] in designing semi-active orthoses has led to a flexible and conducive structure. Another research team has designed an active device by exploiting compliant and flexible dielectric elastomer stack actuators to simplify the wearing of tremor orthoses [63]. Additionally, Hosseini et al. proposed paired piezoelectric sensors and actuators to build more compact and lightweight devices [58].

Additive manufacturing of soft orthoses and materials

Most conventional robots and actuators are based on rigid materials that are not suitable for wearable devices. However, there has been a recent surge of research interest in the use of smart materials and soft actuators in various fields [64, 65]. Even though the manufacture and manipulation of soft robots pose additional challenges, their characteristics—such as low weight and compliance—make them ideal candidates for wearable orthoses [64]. 3D and 4D printing technologies are capable of fabricating complex shapes for robots and actuators with different smart materials [66]. Unlike 3D-printed products that are static, in 4D printing, the fabricated product can change dynamically over time in response to external stimuli [67], making it a better alternative to producing wearables. By utilizing 4D printing, researchers could integrate different parts and functions during manufacturing into active and semi-active wearable orthoses to save time and effort while enhancing the flexibility and customization of the products. Next, we look at sensors and actuators that have already been used in hand tremor orthoses, and recent developments in the fabrication of these sensors and actuators by 3D and 4D printing.

3D/4D-printed sensors

In "Tremor suppression mechanisms" section, different mechanisms for mitigating tremors, including passive, semi-active, and active mechanisms, have been explained. In the semi-active and active mechanisms, the activation of the orthosis is dependent on the presence of different types of hand tremor. The semi-active mechanism is similar to the passive mechanism, with the additional option of an OFF–state in the absence of tremors. Furthermore, in these kinds of orthoses, different parameters of the device, including the friction coefficient and stiffness, are changeable and can be tuned to attenuate tremors of different amplitudes and frequencies. Moreover, active mechanisms for mitigating tremors apply force in the opposite direction of the tremor but at an equal amplitude. Therefore, in semi-active and

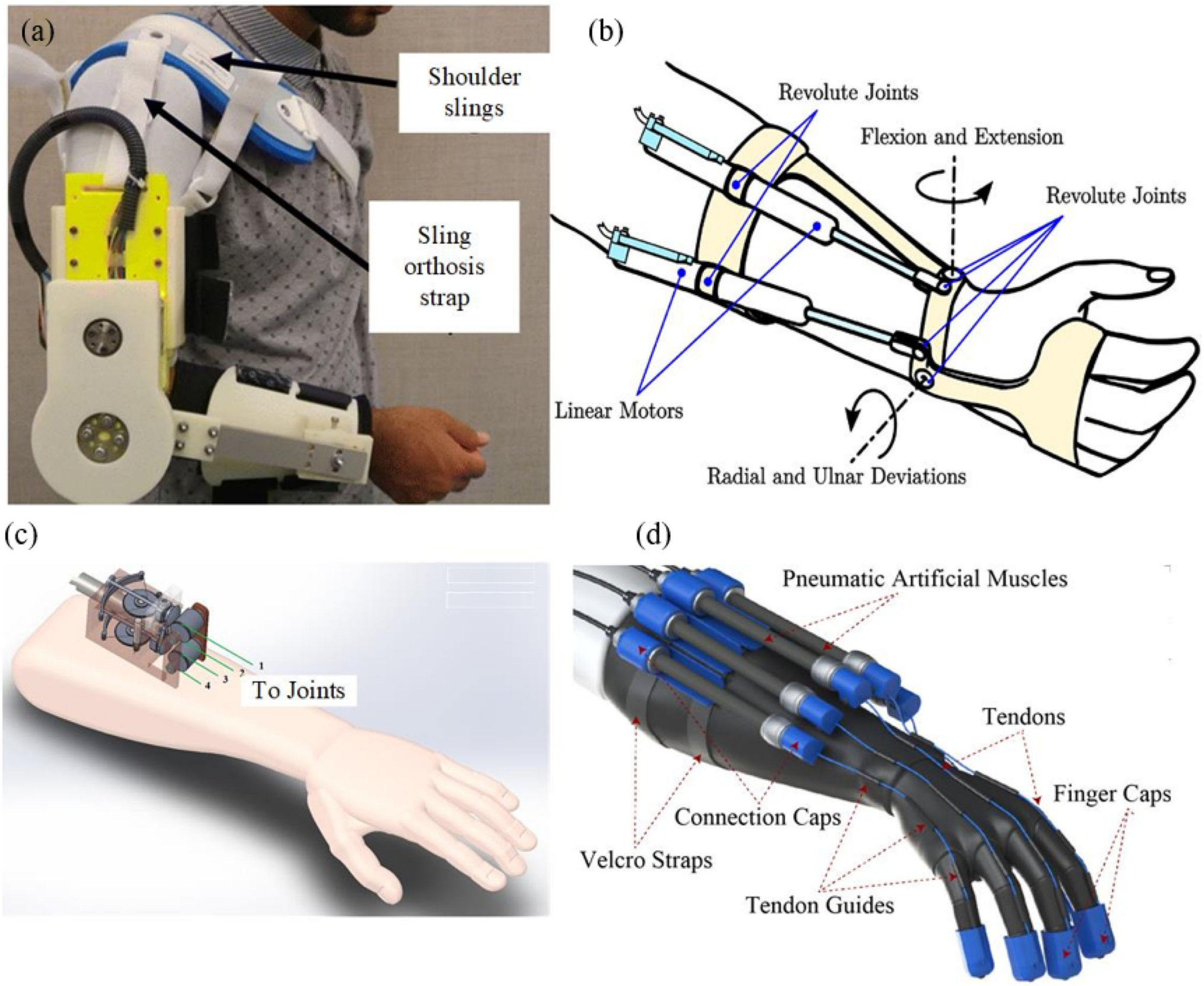

Fig. 4 **a** Tremor suppressor orthosis (TSO) with brushless DC motors (reproduced from [57], Copyright 2019, with permission from the authors, licensed under CC BY 4.0); **b** orthosis with permanent magnet linear motor (PMLM) actuators (reproduced from [59], Copyright 2019, with permission from Elsevier); **c** tremor suppressors with multi-channel mechatronic splitters (MMS) (reproduced from [56], Copyright 2017, with permission from Elsevier); **d** pneumatic artificial muscle (PAM) tremor suppressor (reproduced from [61], Copyright 2021, with permission from the authors, licensed under CC BY 4.0)

active mechanisms whose functions depend on the tremor characteristics, identifying tremors is vital to achieve good performance. Thus, sensors play a primary role in data collection in orthoses to monitor the tremor characteristics.

A wide range of sensors, such as electrocardiogram (ECG) [68], electromyogram (EMG) [69], electroencephalogram (EEG) [70], pressure [71], temperature [72], and strain [73] sensors, have been employed in wearable or implantable devices. For instance, Zahedi et al. and Skaramagkas et al. utilized acceleration sensors in semi-active and active mechanisms, respectively [50, 61]. In 2013, Herrnstadt and Menon exploited gyroscope and potentiometer sensors to gather the tremor data of forearms to suppress flexion/extension in their semi-active device [48]. Herrnstadt et al. used a displacement sensor in their self-constructed exoskeleton to collect tremor data [57]. An electromyography sensor can obtain muscle contraction data, which was utilized for fabricating an electrical orthosis to extract tremor signals from muscle activity [74].

Many manufacturing techniques are available for the fabrication and development of sensors. Common methods include laser cutting [75], photolithography [76], contact printing [77], and 3D printing [78]. Among these, 3D printing has grown in popularity owing to its specific advantages over other methods. In addition, it requires a relatively short production time and includes fewer manual production tasks, implying the possibility of operation without human intervention in the future. Despite the nonlinearity and hysteresis effect of some 3D-printed sensors [79], reports have shown that the additively manufactured sensors can be fabricated with high resolution, accuracy, and repeatability [80]. These make 3D-printed sensors viable alternatives to available solutions. Reusability is another excellent benefit of this approach, which comes without any loss of efficiency or sensitivity [81]. The greatest advantages of 3D printing are quick fabrication, the simple manufacturing process involving a small number of steps, and less human intervention [82]. Zheng et al. recently reported that, even though 3D-printed sensors have disadvantages—such as high cost—and the fact that they still represent an immature technology [83], 3D printing and smart materials have led to the development of 3D-printable sensors with complex shapes that can be integrated with soft orthoses and actuators through various conductive materials, like carbon-based materials [83] and liquid metals [84]. In the early stage of research, conductive materials and circuits were built and embedded in 3D-fabricated structures [85], but as 3D printing technology advanced, both parts were produced by 3D printers [86], making the fabrication process easier, faster, and more economical. In addition, although certain improvements are required for 3D printers to fabricate more precise structures [87], AM exhibits promising results in terms of producing more personalized structures [83] and integrating them into orthoses and prostheses [83, 87]. These advantages of 3D printing render the production process cost-effective and time-saving. In this section, we review recent 3D/4D printing improvements in terms of fabricating sensors; researchers have already tested these types of sensors to study hand tremors, including accelerometers, displacement sensors, and EMG sensors.

Accelerometers

Tremor acceleration is a parameter that has been used to rank tremor severity. Thus, accelerometers are commonly used in upper limb tremor mitigators for data collection [38, 46, 50, 61]. Acceleration usually differs between joints; i.e., each joint's acceleration can vary slightly. Knowing the exact frequency of hand tremor is crucial for tuning hand orthoses to efficiently absorb tremors. Therefore, an ideal 3D-printed accelerometer should have high sensitivity and quick response to timely detect tremors. 3D-printed capacitive accelerometers have been fabricated in the past with acceptable sensitivity (>12 fF/g) [88–90] (Fig. 5a). In another study, an accelerometer based on a Fabry–Pérot cavity was designed and constructed using a 3D printer [91], including a G-shaped mass–spring structure with high sensitivity (183.793 V/g) and resolution (300 ng). The piezoresistive accelerometers were 3D-printed using a stereolithography apparatus (SLA) (Fig. 5b) and fused deposition modeling (FDM), yielding acceptable sensitivities of 11.98572 mV/g and 13 $\mu Vs^2/m$, respectively [92, 93]. Furthermore, a uniaxial Ti6Al4V alloy accelerometer has been proposed that uses laser powder bed fusion (L-PBF), which is small in size and exhibits a sensitivity of 184 fF/g [94].

Displacement sensors

Displacement sensors are utilized in tremor orthoses, such as elbow orthoses, to measure tremor angles [57]. In a group of 3D-printed magnetic displacement sensors, the detection and measurement steps are performed based on the Hall effect [99]. Besides, the effect of eddy currents has been used for measurement in other AM magnetic sensors [100]. Li et al. reported that 3D-printed eddy current sensors have a wider range of linearity than traditional sensors, and their fabrication is faster and cheaper [101]. Recently, a displacement sensor based on a pinhole camera concept (Fig. 5d) was developed, which projects light through the pinhole and affects four photodiodes [95].

Electromyography sensors

Electromyography (EMG) biosensors are placed on subjects' skin to measure electrical pulses from muscle contractions. In tremor studies, EMG sensors are commonly utilized to distinguish tremors from intentional motions. Flexible and soft EMG sensors have been 3D-printed with FDM, and they demonstrated comparable performance to traditional sensors [87, 102] (Fig. 5c).

3D/4D-printed actuators

In upper limb orthoses, actuators aid the motion of or imitate certain body parts. Most traditional actuators are heavy, rigid, and bulky, which makes the accommodating orthoses or prostheses uncomfortable to wear. Recent studies have shown that soft actuators, with low weight and the capacity to impose high forces, have a high potential for application in orthotic and prosthetic devices. Furthermore, AM has enabled the fabrication of soft actuators in complex and customized shapes, with greater production speed [65]. Next, we focus on actuators that have been used in tremor orthoses, and review recent studies on fabricating these actuators via AM.

Pneumatic and hydraulic actuators

Unlike their rigid counterparts, soft actuators are stretchable and flexible, and allow for more comfortable interactions with the human body. The two common soft actuator types used to produce bio-assistant devices are pneumatic [103] and hydraulic [104]. Wirekoh et al. developed a fiber-reinforced bending pneumatic artificial muscle specifically to suppress finger tremors [60]. With recent advancements

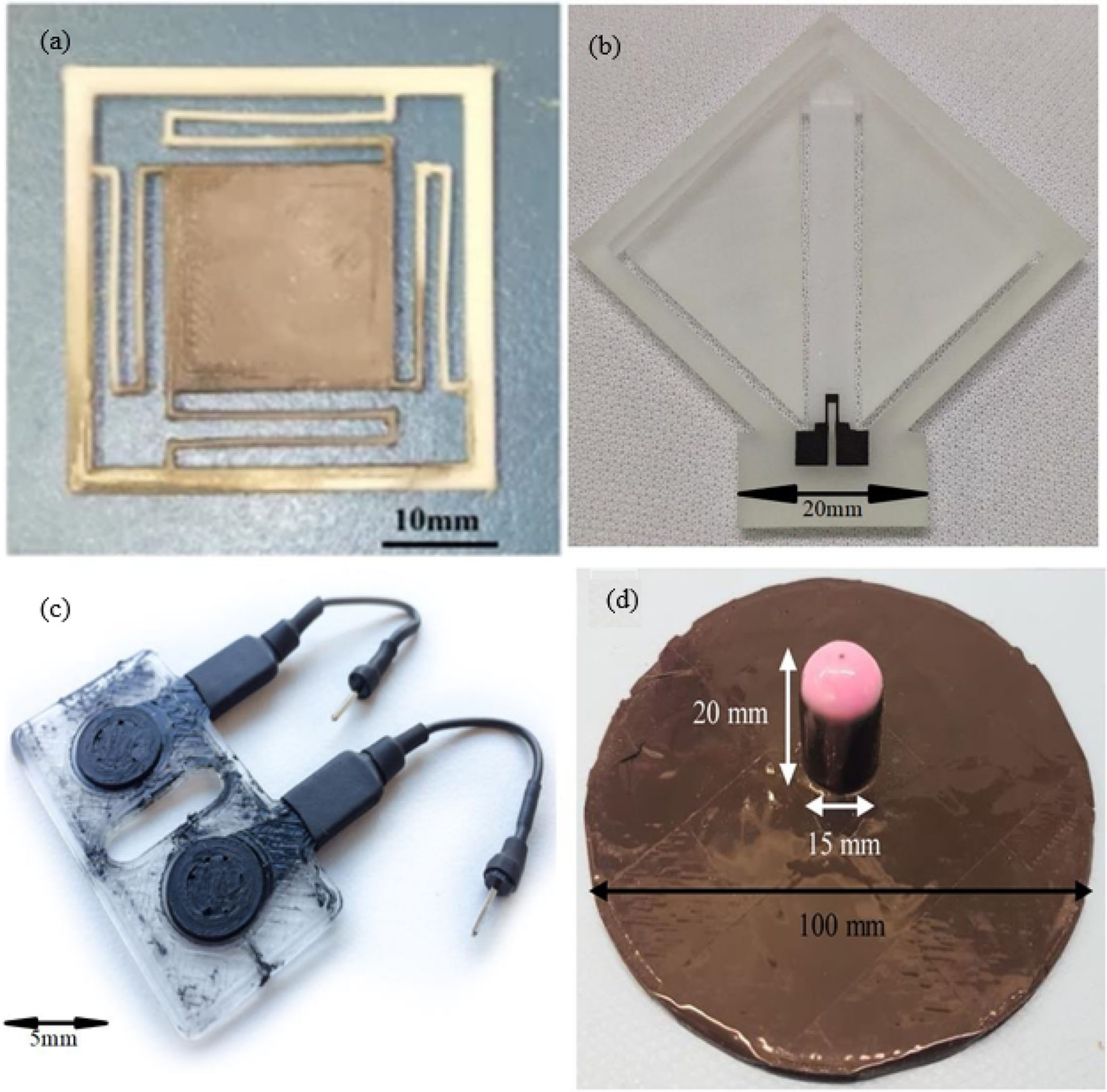

Fig. 5 3D-printed sensors: **a** Capacitive accelerometer (reproduced from [90], Copyright 2021, with permission from the authors, under exclusive license to Springer Science Business Media, LLC, part of Springer Nature); **b** piezoresistive accelerometer (reproduced from [92], Copyright 2020, with permission from the authors, licensed under CC BY 4.0); **c** EMG sensor (reproduced from [87], Copyright 2020, with permission from the authors, licensed under CC BY 4.0); **d** displacement sensor (reproduced from [95], Copyright 2019, with permission from Elsevier)

in 3D/4D printing, it has become possible to fabricate soft pneumatic (Fig. 6c) [98, 105] and hydraulic [106] actuators customized for each patient in different sizes and complex shapes. These 3D-printed pneumatic actuators have shown high (up to 26) payload-to-mass ratios, high actuation speeds, and long lifetimes [107, 108]. Closed-loop 4D-printed soft actuators (a specific type of 4D-printed actuator with a closed-loop controller and embedded sensors) have been developed with embedded 3D printable sensors, and exhibited promising results in controlling robots incorporating recent advancements [109–112], giving them great potential for use in tremor suppression.

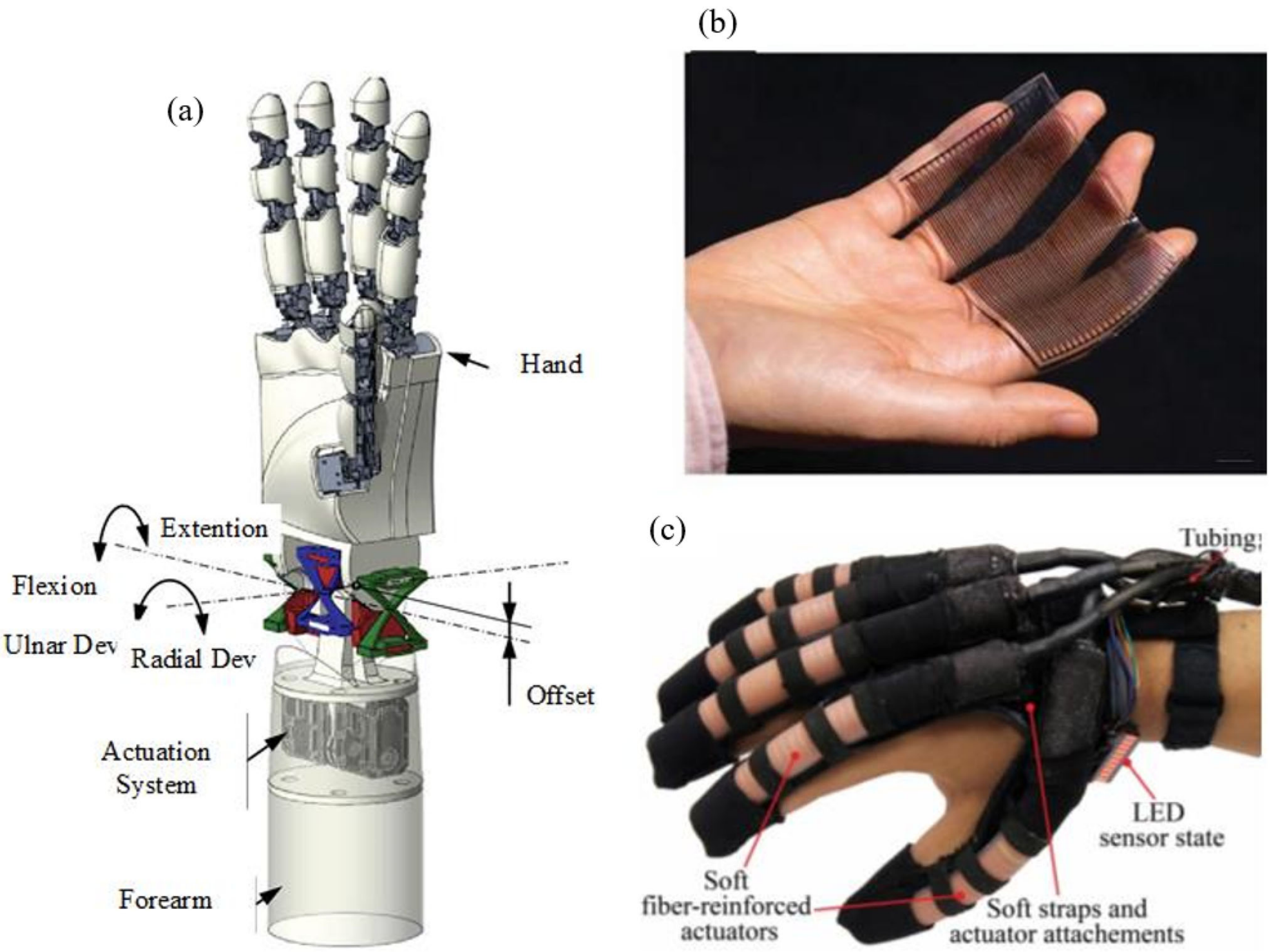

Fig. 6 3D-printed soft actuators and structures: **a** Compliant wrist joint (reproduced from [96], Copyright 2021, with permission from Elsevier); **b** Dielectric actuator (reproduced from [97], Copyright 2019, with permission from Wiley); **c** Hand assistant device with a hydraulic actuator (reproduced from [98], Copyright 2015, with permission from Elsevier)

Shape memory material

Shape memory materials (SMMs) can recover their original shape under appropriate external stimuli. Hand orthoses made of SMMs are efficient in tremor suppression. Shape memory alloys (SMAs) have been utilized in a flexible wearable actuator for hand tremor suppression [113, 114]. Shape memory polymers (SMPs) have significantly contributed to the 4D printing of soft wearable actuators [115], yielding a high recovery rate of 96% [116]. In addition, the integration of SMA and SMP with multi-material printing [117] has resulted in a soft robotic hand, which was reported to work at 0.125 Hz without active cooling and capable of handling heavy objects up to 133 g [118]. Furthermore, SMAs may be more efficient and versatile in soft orthoses embedded with curvature sensors [119] and smart soft composites (SSC) [120].

Compliant mechanism

Compliant mechanisms (CMs) comprise a type of mechanical mechanism that can deform owing to flexible parts [121], which—compared to their traditional rigid counterparts—have certain advantages in terms of fewer parts, reduced weight and cost, lower friction, and lower maintenance costs [122, 123]. Recently, with the ongoing development of AM and material science, great advancements have been made in this field. CMs have the potential to be utilized in hand orthoses; they contribute to compliant joints and actuators to produce counterforces, in order to decrease tremors and design vibration absorption mechanisms. A compliant actuator was fabricated via AM with polypropylene (PP) to passively suppress hand tremors based on friction [124]. In 2017, Choi et al. proposed a 3D-printed compliant finger with an embedded pressure sensor that is lightweight and inexpensive [125]. Recently, an innovative, compliant wrist joint (Fig. 6a) with the ability to undertake ulnar/radial and flexion/extension has been fabricated via 3D printing [96]. Researchers have proposed various compliant mechanisms as attenuators of vibration at known low frequencies [126, 127].

Bistable compliant mechanisms (BCMs) are a special type of CM that can achieve two stable states via the energy stored in their flexures [128]. They have been utilized in different fields, such as switches, closure valves, or circuit breakers [129]. Some hand orthoses, such as SJS [52], operate in both the OFF and ON state, and these BCMs can be utilized as monolithic light switches to shift between states. A BCM with stiff and compliant states has been designed, which can move in linear (Fig. 7a) and circular (Fig. 7b) motions (capable of controlling different types of tremors) while in the compliant state [130]. In addition, in a compliant state, motion can be achieved with near-zero stiffness. Therefore, this mechanism does not affect voluntary motion, and when a tremor occurs, it switches to a stiff state to suppress the tremor.

Electro-responsive actuators

Electro-responsive actuators, such as dielectric elastomers and piezoelectrics, are electrical-responsive materials that have attracted significant attention because of their low weight and flexibility. The successful integration of piezoelectric actuators and sensors to suppress hand tremors has been reported [58]. 3D-printed piezoelectric actuators have shown promising results and can be utilized in micro applications [131–133]. Dielectric elastomer actuators (DEA) have also shown great capability to suppress PD hand tremors [63]. Furthermore, there have been successful reports of 3D-printed DEA [134, 135], with up to 9% actuation strain and a breakdown voltage of about 25 $\mathrm{V}\mu\mathrm{m}^{-1}$ (Fig. 6b) [97]. DEA has also been utilized for vibration damping purposes to suppress high-frequency vibrations with 10–15 dB efficiency, suitable for tremor vibration suppression [136].

Laminar jamming structures

Jamming structures have variable stiffnesses and are typically made of particles, stacked layers, or axially oriented fibers enclosed in an envelope. Recently developed laminar soft actuators have been utilized in hand tremor suppressors due to their ability to mitigate hand tremors both in the wrist [52] and fingers [53]. Various materials, such as paper, elastomers, polyester films, and sandpaper, have been studied as laminar structures to obtain the desired stiffness. Recently, AM was used to fabricate geometrical shapes of envelopes and layers with a complex inner shape via multi-material 3D printing, which are both lightweight and flexible [137, 138]. A tendon-driven finger integrated with laminar jamming made of Dura-Lar film has also been produced via 3D printing, and the results confirmed its high load capacity for an effective vibration attenuator in hand tremors [139].

Magneto-responsive actuator

Magneto-responsive materials, such as magnetorheological (MR) materials, have also shown good efficiency in attenuating tremors in the upper limb in tremor orthoses [49, 50]. The MR fluid has tunable stiffness when exposed to a magnetic field. Recently, the advancement of AM has made fabricating complex shapes and distributed MR structures more feasible [140]. Studies have shown the different damping characteristics of such materials under various magnetic fields in a wide frequency range [141]. A soft beam with tunable stiffness has been developed with an MR fluid embedded in a polyurethane body with a functionally graded design of the MR material [142]. The magnetic field intensity and direction can affect the beam stiffness, and experiments showed a 23% increase in beam stiffness along with higher MR density. Furthermore, 3D-printed MR polymers (MRPs) exhibited different levels of stiffness, shape memory, and thermal healing properties [143].

Variable stiffness materials like MR fluids can be utilized as tremor suppressors in two different settings: (1) a friction-based mechanism (Fig. 8c) and (2) a spring–mass mechanism (Fig. 8d). In friction-based mechanisms, the orthosis connects tremulous parts of the body to non-shaking parts via beams (e.g., in suppressing wrist tremors, the orthosis connects the hand to the forearm) that can move via the variable stiffness fluid; e.g., the Steadiwear glove uses dilatant fluid to mitigate wrist flexion/extension tremor [42]. In this mechanism, tuned friction can eliminate tremors due to the tremor amplitude usually being smaller than the voluntary motion amplitude. In the spring–mass mechanism, a variable stiffness structure can be utilized as a variable stiffness spring, and its stiffness can be tuned to change the natural frequency of the mass–spring to the tremor frequency.

Discussion

Various types of hand tremor-suppression orthoses with passive, semi-active, or active mechanisms have been created to help people with upper limb tremors all over the world. These devices were designed to suppress different types of tremors, such as rest or action tremors in the shoulder, elbow, wrist, and finger joints. The noninvasive, low-cost, and high-performance nature of hand tremor orthoses has made them a practical solution for treating tremors in diseases like PD and ET. Three main strategies have been exploited to mitigate the tremor force in the devices discussed in this paper:

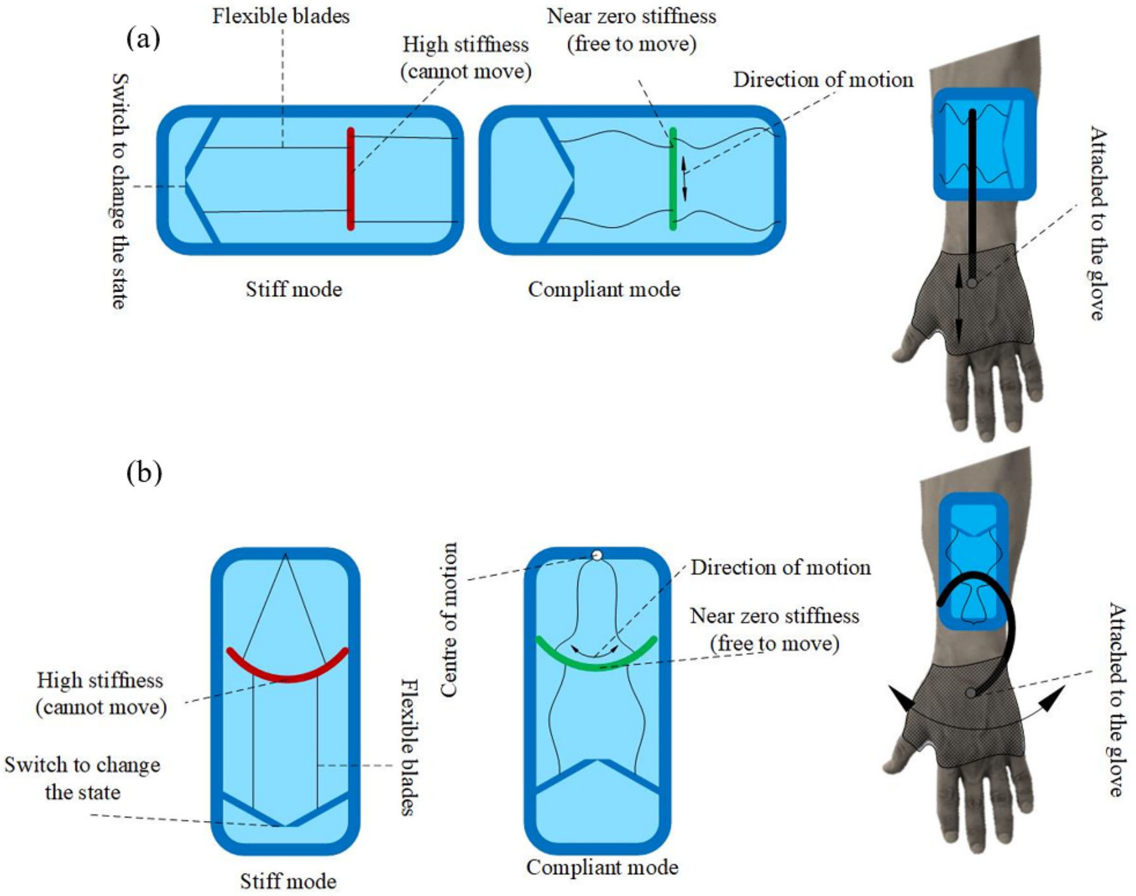

Fig. 7 BCM with linear and circular motion: **a** linear BCM mechanism and its application to control flexion/extension tremors; **b** circular BCM mechanism and its application to control ulnar/radial tremors

(1) friction; (2) mass–spring–damper; and (3) active force. Friction is a passive way to decrease the tremor amplitude. In most patients, the amplitude of the tremor force is relatively small compared to that of voluntary forces. Therefore, a small friction force is a simple way to deal with tremors. However, friction affects voluntary motion; therefore, in some orthoses, a controller deactivates the friction during tremor-free intervals [48]. The tuned mass–spring–damper system is one of the most common strategies to absorb vibration in various fields, and has also been exploited in hand tremor devices. Because of the seismic mass in the mass–spring–damper system, these kinds of orthoses can be heavy. Even though the added mass can have a smaller size, theoretically, the small mass leads to a wide range of motions, which makes the orthosis bulky. Therefore, there should be a trade-off between the mass and volume of the orthosis.

Moreover, mass–spring–damper systems are not suitable for simultaneous use in different types of tremor with different directions because there will be separate seismic masses that are intolerable for patients. In an ideal mass–spring—damper system, the total tremor energy transforms into mass, and it applies a force equal to the tremor force to the limb, which suppresses the tremor. In the active force strategy, researchers analyze the hand tremor signals, extract their characteristics, and then generate and apply a counterforce with different actuators to cope with the tremor. However, most active orthoses use a motor and pump to generate counterforces requiring a high-power energy source, which leads to the device being heavy. Similarly, using various motors or pumps to attenuate tremors in different directions is a challenge that is addressed using the MMS mechanism [56]. Furthermore, using rigid parts for wearable devices is a disadvantage that is overcome by utilizing soft actuators [58, 60].

Conventional tremor suppressors are fabricated using heavy and rigid actuators; however, with the recent advancement of soft actuators, there have been significant developments in hand orthosis design and efficiency. In addition, the latest advances in AM and material science have provided a great opportunity to utilize smart materials in orthoses and fabricate them in complex shapes and structures. Various types of upper limb tremor mitigators have been developed by

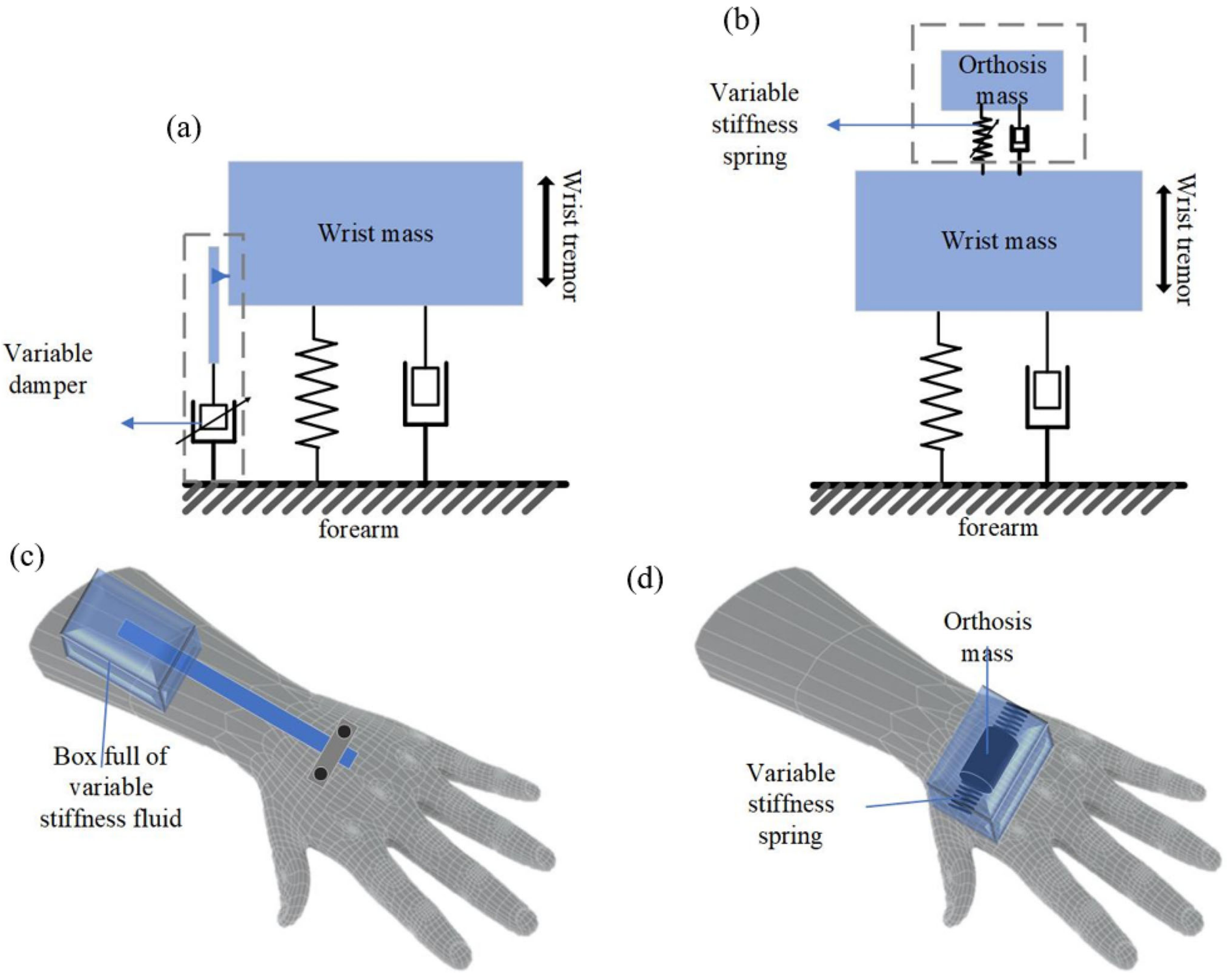

Fig. 8 Variable stiffness material strategies to suppress tremors: **a** Schematic view of friction damper mechanism using a variable stiffness material; **b** schematic view of the mass–spring–damper mechanism using a variable stiffness material; **c** friction damper orthosis concept; **d** mass–spring—damper orthosis concept

the AM of soft actuators, including pneumatics, hydraulics, SMAs, SMPs, CMs, electro-responsive structures, laminar jamming structures, and magneto-responsive mitigators. Although soft actuators like pneumatic, hydraulic, and laminar jamming actuators have a relatively high efficiency, they require heavy or bulky external equipment, such as pumps, which are not suitable for wearable devices. On the other hand, SMM actuators can be utilized in compact and lightweight applications because they are able to generate enough counterforce to attenuate the tremor force. However, these actuators are not rapid enough to change the direction of the counterforce in response to proper stimuli. In this regard, electro-responsive and magneto-responsive variable stiffness materials can be exploited in friction-based tremor-suppression orthoses. Despite their effects on the voluntary motion of the arm and hand, they can still be manufactured with an appropriate size and weight to effectively suppress tremors. Moreover, various integrated sensors, such as accelerometers, displacement sensors, EMG sensors, and electromyography sensors, which have been tested as tremor suppressors, have been explored. Despite that the size of most of the fabricated prototypes of these sensors is larger than commercialized accelerometers, their production cost and time using AM are superior to those of other fabrication methods.

During the design and fabrication of hand tremor suppressors, rigid actuators and motors have been utilized to transform and apply a counterforce to decrease the tremor amplitude, mainly because of their ease of analysis, design, and control. However, these actuators make the device heavy, rigid and difficult to wear, and they typically have a limited DOF that cannot manage complex arm and hand motions. These limitations have led researchers to move towards soft actuators that are lightweight and more flexible; however, analyzing actuator motion in such actuators is more complex due to their DOFs. Recent powerful computers and analysis methods, such as various machine learning (ML) algorithms [144, 145] and finite element analysis techniques [146, 147], have provided researchers with new tools to analyze and design soft actuators. Furthermore, via AM, soft actuators with complex structures could be fabricated to generate the desired force transformations and stiffnesses in different states. In all of the fabricated hand tremor devices to date, sensors and actuators are separate elements that make the devices bulkier, heavier, and requiring final assembly, which can increase the product size, weight, and cost. However, with recent developments in 3D and 4D printing methods, sensors and actuators could be fabricated simultaneously in a monolithic structure that could significantly decrease the device volume.

The high DOFs of soft actuators distinguish them from rigid actuators; as such, significant research attention has been paid to designing an appropriate control strategy for these actuators. In the controller design for soft actuators, besides actuator application, the geometrical shape and structure are the key factors to be considered. As soft actuators are difficult to analyze due to their high flexibility, model-free controllers such as ML techniques have been developed. These controllers can calculate the precise movement by utilizing a few sensors in rigid actuators. However, for such actuators to precisely locate the position of sensors, there should be a network of sensors distributed around the actuator to obtain enough data.

In active and semi-active orthoses, there is a need for compact, high-energy–density, and long-lasting power sources to produce a portable, lightweight, and reliable hand tremor suppressor. The lack of a high-energy–density power source has been a major obstacle of developing portable motor-driven orthoses or pressure-activated actuators, such as pneumatic or hydraulic actuators; such devices have high power demand to suppress tremors. In addition, orthoses are in contact with the human body; hence, these power sources should meet high safety standards. Electro-active actuators, such as dielectric elastomers and piezoelectrics, will be actuated in the presence of high voltage, which should be isolated safely to prevent any undesired effect on the patients' bodies. Furthermore, due to the low voltage output of common power sources, it is necessary to produce safe and compact low-voltage to high-voltage converters in electro-active actuators. Therefore, devising and developing safe, compact, high-power-density power sources is a dominating factor in designing hand tremor orthoses.

Although various hand tremor suppressors have been developed in recent decades, patient acceptance has been poor due to their drawbacks, such as bulky shape and large weight; therefore, the challenges in developing a high-demand, practical, compact, and compliant hand orthosis are still present. We believe that, with the recent developments in AM and advancements in soft actuator design and control discussed in this work, customized 3D-printed tremor orthoses with the characteristics of low weight, compact size, flexibility, smart features, and high efficiency can be further designed to attenuate tremors.

Conclusions

Tremors can lead to difficulty in pursuing normal daily activities and cause depression in patients. Studies have shown that various types of tremor-suppression orthoses are capable of decreasing tremors. In this paper, passive, semi-active, and active mechanisms for tremor suppression were reviewed. Active devices could support voluntary motion and suppress tremors at the same time, but they usually have motors and pumps that make them heavy and bulky, and they also require external power sources. On the other hand, passive orthoses are simple, low-cost, and lightweight, while they can affect voluntary movements. Semi-active devices automatically tune to the frequency of tremors and do not have any effect on arm movements during tremor-free intervals. However, patient concerns still remain due to the bulkiness and large weight of such mechanisms resulting from separate sensors, actuators, and controller units designed for these orthoses. This paper revealed that the fabrication of customized, complex-shaped, multi-material orthoses, and prostheses can be realized with the recent advancements in AM and improvements in smart materials. In addition, it was discussed how the integration of 3D/4D printing, smart material science, and their modeling and embodiment control features could be used to make more efficient and comfortable tremor-suppressing devices.

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Author contributions MM and AZ were involved in conceptualization, writing—original draft, and visualization; AZ, MB, YX, and AZK helped in supervision, funding acquisition, and writing—review & editing.

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Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This article does not contain any studies with human or animal subjects performed by any of the authors.

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