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Review

Haptic Systems: Trends and Lessons Learned for Haptics in Spacesuits

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Abstract: Haptic technology uses forces, vibrations, and movements to simulate a sense of touch. In the context of spacesuits, proposals to use haptic systems are scant despite evidence of their efficacy in other domains. Existing review studies have sought to summarize existing haptic system applications. Despite their contributions to the body of knowledge, existing studies have not assessed the applicability of existing haptic systems in spacesuit design to meet contemporary challenges. This study asks, "What can we learn from existing haptic technologies to create spacesuits?". As such, we examine academic and commercial haptic systems to address this issue and draw insights for spacesuit design. The study shows that kinesthetic and tactile haptic systems have been effectively utilized in various domains, including healthcare, gaming, and education to improve the sense of touch and terrain and reduce sensory deprivation. Subjective and objective evaluation methods have been utilized to assess the efficacy and safety of haptic systems. Furthermore, this study discusses the usefulness, safety, and applicability of haptics in spacesuits and the implications for research into space haptics.

Keywords: EVA; electro haptics; haptics; Mars; spacesuit; human factors

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1. Introduction

Haptic technology is a type of assistive technology that uses a sense of touch to convey information to the brain and spinal cord via the use of forces, vibrations, or movements [1]. Due to their ability to improve cognitive load deficiencies [2], haptic systems are used in various industries, including consumer products and medicine [3]. Indeed, it has been shown that the skin's touch receptors may transmit a wide range of information, such as instructions, words, and more [4]. For example, recently, a sensory wristband that substitutes sound for touch has been proven to activate the auditory and somatosensory areas of the brain. As such, the brain quickly enlists the regions responsible for hearing to help interpret the touch [5].

In the context of spacesuit design, attempts to utilize haptic systems remain limited despite evidence of their effectiveness [6]. The current design of spacesuits reduces astronauts' mobility and leads to sensory deprivation since the suits are thick (10–30 mm) and have up to 16 layers [7]. Audio-visual sensory deprivation impairs awareness, cognition, and visuotactile peri-personal space [8], possibly leading to falls or near falls due to the inability to read the terrain in space [9]. Because of these restrictions on the human senses, astronauts may find it more difficult to concentrate on the primary Extra-Vehicular Activities (EVA) that are performed by astronauts in outer space outside a spacecraft such as collecting geological samples or setting up and testing scientific instruments [10]. A few attempts have been made to incorporate haptics into spacesuits to mitigate the sensory deprivation issue, among other issues. Examples include a cap [2], gloves [10], and shoes [11] that utilize haptics. However, these attempts are still in their initial stages and minimal evaluation has been conducted to prove their efficacy.

Existing review studies have attempted to summarize current efforts to apply haptic systems in various contexts. For example, Yang et al. [12] investigated the viability of active material-based haptic technology for use in virtual reality (VR) and augmented reality (AR) applications, while another review study primarily looked at the challenges of the wearability of haptic devices and discussed the design concepts for wearable interfaces [13]. Existing review studies reveal that haptic systems show promise in various industries, although several obstacles still need to be overcome. However, despite their contribution to the research community, few studies have analyzed existing evidence-based haptic systems to draw inspiration for incorporating haptics into the design of spacesuits to address current challenges.

This study aims to answer this research question, "What can we learn from existing haptic systems to design spacesuits?" To address this question, we examine haptic systems currently used in academic and industrial settings, drawing insights for spacesuit design.

The remainder of this article is structured as follows. Section 2 reviews the related work, whereas Section 3 presents the current space mission challenges and the methods used to address them. Section 4 explains the methodology for reviewing the academic and industrial haptic systems and the research questions. Section 5 presents the results, and Section 6 discusses the findings and issues relevant to spacesuit haptic design. Finally, Section 7 concludes the study.

2. Literature Review

In recent years, several studies have reviewed various types of haptics in different contexts. Table 1 provides an overview of these review studies. For example, ref. [14] predicted that easy-to-use haptic gadgets will replace traditional equipment. However, low awareness and hefty installation costs limit their adoption. Despite their fast growth, haptic systems still face considerable obstacles and restrictions. As such, industrial applications must enhance design complexity, feedback quality, and operation safety, and health sciences must increase patient safety, affordability, and regulatory clearances. The study also found that current VR systems have poor haptic input, which causes difficulty in modeling and interacting in a computer-synthesized environment. In healthcare haptic applications, surgeons are often unsatisfied with the tactile feedback provided. Another study, ref. [15], explored haptics in various domains, including healthcare, concluding that haptics is the study of sensing human touch through kinesthetic and cutaneous receptors and that haptic technology is a fast-growing and dynamic field of research that has seen commercial success in entertainment, medical simulations, and design. Nonetheless, ref. [15] also showed that commercial haptic actuators are restricted in availability and expressiveness. As such, many researchers build their own using off-the-shelf components. Another review study [16] found that several challenges must be addressed for surface haptic displays to achieve mass market adoption, including high transparency (allowing visual information to be delivered to the user in synchronization with tactile feedback), a large tactile interaction area, simultaneous tactile feedback displayed in different directions, simultaneous tactile feedback stimulating different receptors, low power consumption, and easy integration and compact design.

Table 1. An overview of review studies on haptics.

No.	Haptic Type and Context	Research Focus	Findings	Limitations	Reference
1	General	- Classifying haptics in terms of functionality and construction. - Challenges of adoption.	- Lack of awareness and high cost hinders adoption.	- No discussion of the evaluation of haptic systems. - No discussion of haptic applicability in space.	[14]
2	Active material-based haptics with an emphasis on immersive applications	- Trends of haptics - Future of immersive application demands.	- Haptics are popular in the industry because of vibrotactile feedback with high spatial resolution, dynamic range, and output intensity.	- No discussion of the evaluation of haptic systems. - No discussion of haptic applicability in space.	[12]
3	General	- Haptic system design and neurobiology and perception of touch.	- Haptics can be used in mobile communication, navigation, virtual reality, and gaming. - Significance of human touch perception capacity throughout the design process to create usable and effective haptic devices.	- Limited discussion of the evaluation of haptic systems. - No discussion of haptic applicability in space.	[17]
4	Wearable haptic systems for the fingertips and hands	- Applications of haptics in social interactions, healthcare, virtual reality, remote help, and robotics.	- The wearability of a haptic device is determined by its form factor, weight, impairment, and comfort. - Haptic devices may now be used daily due to their wearability.	- Limited discussion of the evaluation of haptic systems. - No discussion of haptic applicability in space.	[13]
5	General haptics in psychology, neuroscience, robotics, and virtual reality.	- The application of robotic haptic interfaces in distant or virtual worlds.	- Haptic technology is a rapidly developing field with commercial success in entertainment, medical simulations, and design.	- No discussion of the evaluation of haptic systems. - No discussion of haptic applicability in space.	[15]
6	Affective haptics	- Recent advances in affective haptics and discusses how touch can alter human emotions.	- Haptic stimulation can enhance media immersion and emotional telepresence. - Haptics is good for communicating valence and arousal, particularly the emotions of happiness, sorrow, rage, and fear. Disgust and surprise have received less attention.	- Limited discussion of the evaluation of haptic systems. - No discussion of haptic applicability in space.	[18]
7	Tactile interactions of human fingers or hands with surface-haptics displays	- Surface haptics that turn passive surfaces into active ones. - Human perception of tactile stimuli exhibited on active touch surfaces.	- For surface haptic displays to reach the mass market, they must have high transparency, a large tactile interaction area, simultaneous tactile feedback displayed in different directions, simultaneous tactile feedback stimulating different receptors, low power consumption, easy integration, and compact design.	- Limited discussion of the evaluation of haptic systems. - No discussion of haptic applicability in space.	[16]

Some review studies assessed specific types of haptics in certain contexts. For example, Yang et al. [12] assessed active material-based haptic technology for VR/AR applications. The study discussed advances in active material-based haptic interfaces, haptic actuation techniques, and devices for major tele-haptic technologies. Touch-based, wearable, skin-attachable, mid-air, and neuro-haptic interfaces were shown to dominate the scene. The study concluded that AR/VR applications need bidirectional, multimodal tele-haptic interactions to enable remote users to communicate through touch. Further, fully immersive tele-haptic interactions need accurate tactile sensations. The study examined current fundamental tactile actuation technologies and their implementation problems and prospects. Another review study examined haptic device wearability issues and presented wearable interface design principles [13]. According to the authors, form, weight, impediment, and comfort define haptic device wearability. Therefore, the study recommended the use of smooth patterns that match the body's natural form. Furthermore, the study found that the weight should match the musculoskeletal support of the body part that it is worn on. Additionally, wearable interfaces should be comfortable and naturally fitting without harming or interfering with the body. Haptic systems have also been effective in media immersion and emotional telepresence [18]. Indeed, haptics can communicate valence and arousal, particularly the emotions of happiness, sorrow, rage, and fear.

In short, current review studies demonstrate the potential of haptic systems in various fields while also highlighting several challenges that need to be addressed. However, despite their contributions to the body of knowledge, most review studies have not focused on reviewing the evidence supporting existing haptic systems. Furthermore, no study has addressed the applicability of existing haptic systems for space exploration. As such, this study addresses this gap by examining evidence-based haptic systems in both academic and industrial settings across different domains and drawing lessons that can be applied to the design of haptic systems for space exploration.

3. Current Space Mission Challenges and Attempts to Address Them

EVA, also called a spacewalk, refers to any activity performed by astronauts outside their spacecraft. Through these activities, astronauts can conduct valuable experiments and test equipment in space. However, EVAs face numerous challenges, including microgravity, extreme conditions, the nature of dust on Mars and the Moon, and ultraviolet lights. The following subsections discuss the challenges and the attempts to address these challenges with detailed spacesuit or space footwear design requirements.

3.1. Microgravity and Fall Incidents

Falling accidents are one of the most pressing challenges for spacewalks due to microgravity. For instance, there were many challenges during the Apollo lunar mission, including 27 falls and 21 near falls [7]. These falls were attributed to low lunar gravity and the Apollo spacesuits, which decreased the range of motion and changed the center of mass due to the built-in portable life support system. The authors concluded that mitigating falling risks in new spacesuit designs is crucial.

A study by Weber et al. (2021) showed sensorimotor performance changes under microgravity conditions during a manual tracking task that required precise and continuous motion changes [19].

Another common challenge of spaceflight is the body's geometric changes due to microgravity. These changes are related to a spinal elongation that straightens the spinal curvature [20–22]. Indeed, according to a study [23], there are accounts of astronauts finding it hard to put on their suits after spending long periods in microgravity environments [22]. On average, the increase in stature is 2.4 cm. However, after the early increase in stature, the astronauts had a small reduction in stature throughout the mission. After the flight, the stature was the same as it was before the flight. Other changes in microgravity include the circumference of hips and thighs being reduced during spaceflight from 7% to 10%.

Another interesting challenge due to microgravity is that the metabolic workload can increase, resulting in more nutrition and hydration demands under microgravity conditions [24].

Moreover, astronauts working in microgravity environments must stabilize and secure themselves at a worksite so they do not float away [25].

McCormack and Phillips-Hungerford (2017) highlighted that future space-footwear technology should allow for comfortable and secure restraint while providing sufficient protection to decrease the chances of foot injury in a harsh microgravity environment. The authors concluded that this technology must adopt a holistic approach to human-centered design and the related occupational health and safety issues in space [26].

Due to the changes in body geometry in microgravity, Kim et al. [23] stated that it is crucial to test spacesuits in an environment that simulates microgravity such as underwater, where astronauts would perform reach motions. This kind of testing should be considered for musculoskeletal and biomechanical stress evaluation.

To prevent astronauts from floating away in space during EVAs, restraint and mobility aids allow astronauts to stabilize themselves. These mobility aids must not have sharp edges to avoid damage to the spacesuit [25].

Weber et al. (2021) argued that the solution to sensorimotor performance changes under microgravity conditions is subtle haptic forms in the form of low stiffness and damping. These haptic forms may be needed when human operators are exposed to non-nominal gravity environments such as on the Moon or Mars and must perform amid the ongoing adaptation to the altered conditions [19].

Shen et al. (2018) proposed requirements and preliminary design specifications for a spacesuit able to record the dynamics and kinematics of human–spacesuit interaction. The objective was to study the interactions between a spacesuit and the wearer to gain insights into spacesuit injury [27].

Hagengruber et al. (2017) presented a lightweight arm-wearable device equipped with an interface based on electromyography (EMG) that generated three-dimensional (3D) control signals from voluntary muscle movements of the operator's arm. They analyzed the influence of microgravity on task performance during a two-dimensional (2D) task on a screen. The user study showed that weightlessness only slightly affected the usage of the interface [28].

MIT's Department of Aeronautics and Astronautics (AeroAstro) and the Charles Stark Draper Laboratory in Cambridge, Massachusetts, are developing a space boot with built-in sensors and haptic motors that vibrate to guide the wearer around or over obstacles [29]. The application can also be used for visually impaired people. The researchers had envisioned that vibrations could indicate the distance to obstacles, as measured by sensors built into the boot. The design of the boots is promising but it has its shortcomings. First, the researchers found that subjects struggled with identifying increases in vibration intensity when distracted in cognitive tests. Second, the boots do not help the astronauts feel the terrain as they can only detect obstacles.

3.2. Sensory Deprivation

Due to their thickness, which ranges from 10 to 30 mm, and the fact that they can have up to 16 layers, astronaut suits can impair the astronauts' dexterity and senses, namely (i) grasping dexterity, (ii) proprioception, and (iii) cognitive ability due to sensory deprivation [7]. Wearing an Extravehicular Mobility Unit (EMU) suit, which is an anthropomorphic spacesuit that functions independently and offers protection from the environment, mobility, life support, and communication to astronauts who perform EVAs while in the Earth's orbit, is necessary during missions but significantly limits the mobility and dexterity of astronauts. The suit makes joints stiffer and more force is required to perform tasks. The gloves are especially important since most operations involve using the hands. The stiffness of the suit is most noticeable in the hands and fingers, leading to increased fatigue and reducing the duration of EVAs.

A study [8] investigated whether reducing external sensory information would affect self-perception, interoceptive accuracy, and the perception of the space around the body. Twenty participants were exposed to 15 min of audio-visual deprivation and performed tasks related to peri-personal space (PPS), which is the space in which we exist and can interact with external entities such as objects or other individuals. The results showed that although PPS became ill-defined after deprivation, interoceptive accuracy was unaltered at a group level, with some participants improving and some worsening. However, changes in PPS were related to interoceptive accuracy and self-reports of "unusual experiences" on an individual subject basis. This suggests a relationship between the malleability of PPS, interoceptive accuracy, and an inclination toward aberrant ideation often associated with mental illness.

RoboGlove is an assistive device that enhances human strength and endurance and can be used for rehabilitation. It is based on the Robonaut 2 system that was developed by General Motors and NASA. The device is lightweight and uses an actuator system to transfer the load from human tendons to artificial ones in the glove. RoboGlove can handle steady-state loads of up to 15–20 lbs and peaks of up to 50 lbs. The device is integrated into a spacesuit glove to help reduce fatigue during spacewalks. RoboGlove has tactile sensing, miniaturized electronics, and onboard processing, making it suitable for use in many industries [30].

3.3. Ultraviolet Rays

Another well-known challenge faced when performing EVA tasks is ultraviolet (UV) rays. Richardson and Stevens (1976) [31] conducted measurements using the guarded hot-plate method on samples of the Skylab boot sole and insulation for a balloon-borne UV spectrometer. The authors concluded that there was very little difference between the boot sole and heel performance under lunar daytime conditions. The heat flux per unit area was high (about 50–60 Btu/ft hr) and the lunar temperature of the boot sole was high (only about 4–5 °F below the temperature on the outside surface of the boot sole). As such, the inner liner of the boot must provide thermal protection. Furthermore, the spacesuit cooling system that maintains the astronaut's body temperature within normal ranges by allowing cool water to circulate through the tubes must be able to remove the high heat load. The astronaut loses heat through his boot soles under lunar nighttime conditions, making the inside temperature of the boot very low (−114 °F to −183 °F). Consequently, the inner liner must be able to provide the needed protection.

A possible method for addressing the UV challenge is to carefully choose the materials from which spacesuits are made. It is critical to build a sufficiently robust spacesuit to allow for multiple EVAs under extreme UV light exposure without damaging the material properties or negatively impacting the suit's functionality and mobility [32]. NASA conducted ground testing on current and new spacesuit materials when exposed to 2500 h of Mars-mission equivalent UV to select materials for the rover and understand the effects of Mars-equivalent UV exposure. NASA tested nine materials, most of which lost tensile strength after UV radiation and became more brittle with a loss of elongation. Changes in chemical composition were seen in all radiated materials through spectral analysis. The results of this test were that NASA selected six materials to fly on the Mars 2020 rover: Orthofabric, Teflon, nGimat-coated Teflon, Dacron, Vectran, and Polycarbonate. All these materials passed the off-gas requirements.

3.4. Cosmic Rays

The shift toward planetary exploration, particularly missions to the Moon and Mars, raises concerns about radiation as a major hazard for personnel in space. Solar particle events and galactic cosmic rays are two sources of ionizing radiation that could impact a mission outside Earth's magnetic field. Exposure to such radiation may lead to various health problems, including an increased risk of cancer in astronauts. The radiation risk for humans in space can affect mission success and result in long-term health effects. It is directly related to the amount of exposure, which is influenced by the mission duration and environmental factors [33]. Long-term space exploration missions risk astronauts' cardiovascular health due to the complex and inaccessible space radiation environment. A study exposed mice to simplified Galactic Cosmic Ray (GCR) irradiation and found that a single exposure to GCR5-ion resulted in significant impairment in cardiac function, including increased arterial elastance likely mediated by a disruption of the elastin fibers. These findings suggest that exposure to GCRs can lead to long-term cardiac structure and function deterioration, increasing the risk of morbidity and mortality for astronauts during deep space missions. These results highlight the need for further research and health considerations when preparing for space exploration [34].

Careful mission planning and surrounding crew habitats with sufficient absorbing matter can help reduce the risk [33].

To accelerate the understanding and mitigation of the health risks faced by astronauts, NASA has developed a GCR Simulator capable of generating a spectrum of ion beams to simulate the primary and secondary GCR fields experienced at human organ locations within a deep-space vehicle. The simulator exposes cellular and animal model systems to 33 sequential beams, comprising protons, helium, and heavier ions. It delivers a 500 mGy exposure that takes approximately 75 min, and sequential field exposures can be divided into daily fractions over 2 to 6 weeks. The NSRL completed the first operational run using the GCR simulator on 15 June 2018 [35].

3.5. Musculoskeletal Injuries

Astronauts can suffer from EVA musculoskeletal injuries during spaceflight, as mobility inside the spacesuit is limited because the gas-pressured spacesuit is stiff in space [36]. A possible cause of these injuries is an increased cognitive load that reduces postural sway [37], which provides the needed sensory feedback to maintain postural stability. Another crucial challenge that spacesuits and space boots must address is that space missions require the manipulation of objects much larger than the crewmember. This type of activity leads to loads on the astronaut's EMU and foot restraint. A study [38] reported a test to define the maximum loads on the EMU resulting from manipulating massive objects. The study reported that significant EMU restraint system loading occurs due to manipulating massive objects during an EVA when the astronaut is in fixed foot restraints. The study identified a safety concern, particularly when the Lower Torso Assemblies (LTA) falls below a safety factor of 2.0, wherein an astronaut has one foot in the foot restraint.

Foot contusions and incidents of misalignment, known as heel-lift, where the heel is raised inside the boot as the heel begins to lift off the ground, have been reported throughout walking trials [39]. This could cause overextension of the ankle or foot dorsum bruising.

To address musculoskeletal injuries, particularly hand fatigue, Dansereau et al. proposed an Extramuscular Augmented Spacesuit Glove (EMAG) that utilized a hand exoskeleton to support phalangeal flexion and reduce hand fatigue and the risk of musculoskeletal injury [40]. The design aimed to improve astronauts' productivity when performing EVAs. The EMAG is based on voltage-controlled soft electro-hydraulic actuators converting electrostatic forces into linear motion. The advantage of using such actuators is that they are lightweight, more precise, and made of safe materials.

Pantaleoni and Lacey (1992) proposed a flight rule for EVA missions, which requires astronauts to keep both feet in the foot restraints during all satellite handling operations. This rule was created to address the safety concerns related to the use of foot restraints. Furthermore, the authors concluded that boot design must take into account the safety of the astronauts during satellite man loads [41].

To address the issue of foot shape changing during gait, the authors in [39] contributed a framework to incorporate foot shape data into spacesuit boot design to enhance comfort and fit. The data identified foot shape changes during gait as a factor that may affect shoe comfort and fit. The study also found that the shape changes involved a heel contour alteration and a reduction in the middle section of the foot.

To simulate floating in space, NASA uses a neutral buoyancy laboratory where astronauts practice performing EVAs [42].

According to NASA, working in the NBL is similar to working in space but with two significant differences: (1) Although buoyant, the trainees still feel the weight of the suit in the NBL, and (2) The trainees also feel water drag/friction that is not encountered in space. Despite these two differences, NASA believes that working below the surface in neutrally buoyant conditions is an ideal way to train for the zero-gravity environment of space.

3.6. Extreme Temperatures

The baseline temperature of outer space is 2.7 kelvins (−270.45 °C; −454.81 °F) [43] which is uninhabitable to life. Indeed, the temperature on the Moon ranges from −378 °F to 253 °F [44], whereas the temperature on Mars ranges from −225 °F to 70 °F.

Existing spacesuits use an Integrated Thermal Micrometeoroid Garment (ITMG), which is the outer layer of a spacesuit. The ITMG insulates the astronaut and protects them from heat loss to guard against damaging solar radiation, micrometeoroids, and other orbital debris, which could damage and depressurize the suit [45].

Belobrajdic et al. [24] proposed a spacesuit design considering thermal regulation and humidity control using a spacesuit water membrane evaporator, full-body radiator, liquid cooling ventilation garment, and variable geometry radiators. Furthermore, the design considered radiation shielding using Radiation Protection Garment (PERSEO Project), biological countermeasures, magnetic shields, hydrogenated boron nitride nanotubes, and FLARE Suit.

3.7. Lunar/Martian Dust

Spacesuits are potentially the main "carrier" of lunar soil particles into spacecraft/habitat-pressurized environments [46]. Lunar and Martian dust are also susceptible to magnets. Tiny metallic iron (Fe0) specks are embedded in each dust particle's glassy shell. Therefore, lunar dust tolerance is considered one of the main challenges. Concerning the evidence from the Apollo missions to the Moon, the continuous contact of joints with dust from the Moon can cause damage to rotation bearings in spacesuits [47]. It was found that rotating bearing mechanisms started to operate with increased friction due to lunar soil contamination.

Several studies have presented proposals to address the issue of lunar and Martian dust. A noteworthy example is the work reported in [48], where the authors used Electrodynamics Dust Shield (EDS) active technology and Work Function Matching Coating (WFM) passive technology created by NASA for rigid surfaces. The researchers also used carbon nanotube (CNT) flexible fibers to build a dust removal system into a spacesuit. As another example, Manyapu et al. [49] proposed a dust removal system for spacesuits. The system uses carbon nanotube (CNT) fibers embedded within the spacesuit's outer layer.

Belobrajdic et al. (2021) presented a spacesuit that can mitigate dust through spacesuit-integrated carbon nanotube dust ejection/removal, an electrodynamic dust shield, photovoltaic dust removal technology, and an electron beam.

Tisdal et al. [50] proposed a panel collection that requires 8 watts of power. The panels use an Electrodynamic Dust Shielding (EDS) modular system to address the lunar dust issue. The EDS uses electrodes that induce an electric field to remove dust particles.

Another study utilized a device using magnetic force to clean lunar dust adhering to spacesuits [51]. Nevertheless, the dust capture was low (40%) despite a high separation of 90%.

4. Methodology

4.1. Research Questions

This study's objective is to offer a non-systematic overview of recent research discussing haptic technology that considers human factors to draw inspiration for haptics in space. The following research questions are explored in this research:

- RQ1: What are the problems that the haptic systems attempted to solve?
- RQ2: What technologies have been used and in what contexts?
- RQ3: What are the existing approaches to haptic systems?
- RQ4: What are the limitations of the existing haptic systems?
- RQ5: What evidence exists to support the validity of haptic systems?

RQ1 seeks to identify the practical problems that haptic systems address. These issues may vary and could be related to health or any field that requires human augmentation. This research question aims to provide insights into the areas where haptic systems have been utilized to improve human experiences. RQ2 aims to explore the technologies used to develop haptic systems, including the types of haptics and actuators. This research question seeks to provide a detailed understanding of the different technologies utilized in haptic systems and how they have evolved. RQ3 focuses on the approaches used to solve practical problems using haptic systems. These approaches refer to the mechanisms utilized in haptic systems to address various issues such as providing sensory feedback, enhancing human–machine interaction, or improving human performance efficiency. RQ4 identifies the limitations and challenges reported by the various authors in the development and implementation of haptic systems. This research question seeks to provide an overview of the problems in existing haptic systems and how they can be addressed to improve the effectiveness of these systems. RQ5 aims to examine the evidence that supports the validity of haptic systems. This research question explores the various methods used to evaluate haptic systems, including experiments, questionnaires, and evaluation studies, to substantiate the effectiveness and practicality of haptic systems.

An extensive search has been conducted to address these five questions, as discussed in the subsequent sections.

4.2. Research Process

The search for the various existing approaches to creating a wearable haptic system for a variety of applications involved searching two different types of databases and repositories: (1) academic and research databases, and (2) educational and technical reports, articles, and websites.

4.3. Inclusion Criteria

The search criteria applied throughout the search process were as follows:

- IC1: The included haptic system research must have been published between January 2012 and December 2022.
- IC2: The haptic system must be a wearable haptic for the fingers, hands, or feet.
- IC3: The haptic system must allow users to manipulate objects virtually while receiving haptic feedback.
- IC4: The haptic system must have an application in space exploration, healthcare, gaming, or education.

4.4. Academic Search Database

The first step was to investigate the most recent research projects in the field of haptics to understand the methodologies and potential tools used. This would highlight tried-and-true designs and methods largely confirmed by empirical research. The following databases were searched: Google Scholar, IEEE Xplore, Springer Link, and Science Direct. Our search focused on designs and experiments for wearable haptic feedback systems to draw inspiration in the context of space.

4.5. Technical and Educational Reports, Articles, and Websites

To broaden the scope and find additional haptic systems, it was crucial to explore alternative sources beyond academic search databases. Our search involved conducting comprehensive online searches utilizing Google's search engine to locate relevant reports, articles, and commercial websites that presented haptic systems for various applications, including but not limited to gaming, leisure activities, and healthcare. The searches enabled the identification of commercially available haptic solutions in various applications.

4.6. Data Analysis

This study used our research questions to guide our analysis of data gathered from websites, academic articles, and reports about creating haptic devices using various methodologies over time. We employed an inductive methodology, concluding with specific examples to inform more general themes and approaches. This approach allowed us to provide enough examples to understand each design or technique without the need to list every approach that fell under a particular category. Our focus in this study was to report the limitations of the methodologies and designs outlined by the authors of the respective studies we analyzed. By providing this information, we aim to contribute to a better understanding of the strengths and weaknesses of each haptic device design or methodology, which can inform future research and development in this field.

5. Results

Figure 1 shows the number of published studies included in this paper by year. Most papers are from 2018 and 2020 and there are a few more recent papers from 2021 and 2022. Table A1 (Appendix A) shows the academic and commercial haptic systems.

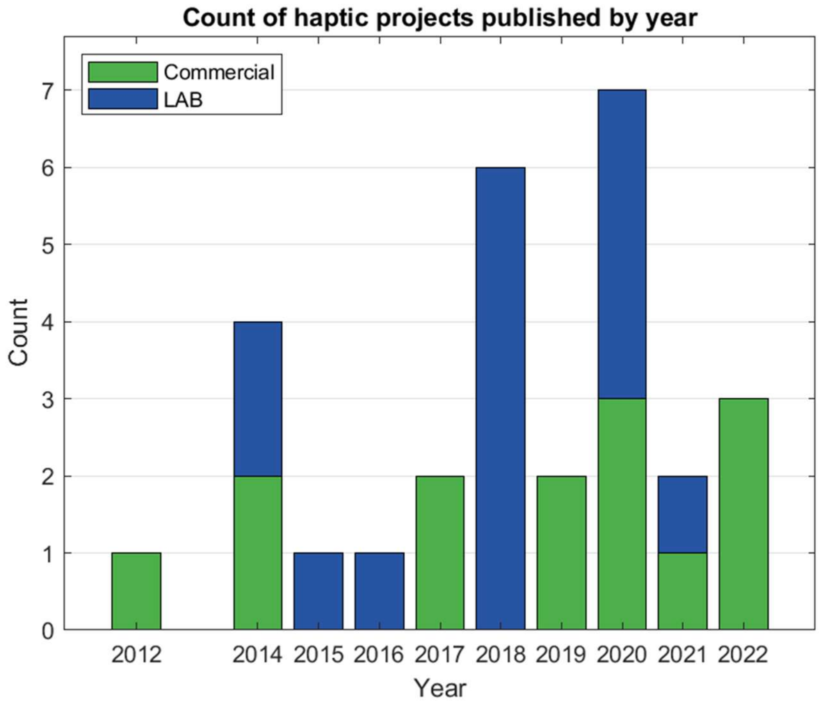

Figure 1. The number of academic and industrial studies included in this paper by year.

5.1. What Are the Problems That the Haptic Systems Attempted to Solve?

Haptic systems have been used to solve various problems, including gait analysis, object grasping, a sense of virtual terrain, and a sense of touch in a virtual reality (VR) environment (Figure 2).

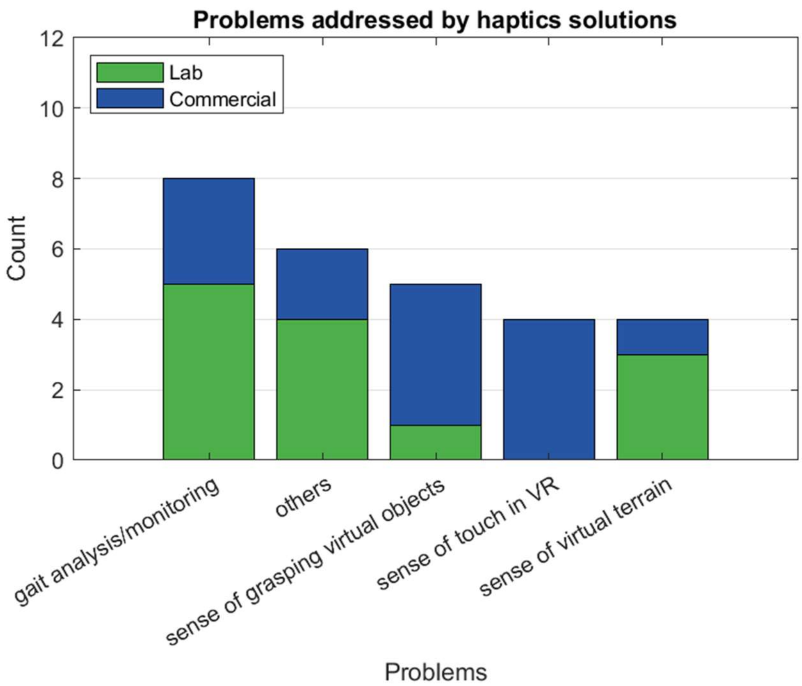

Figure 2. Problems addressed by haptic solutions.

Concerning gait analysis, several studies attempted to design haptic feedback systems for gait monitoring and improving gait performance. For instance, the study reported in [52] designed a smart insole for monitoring plantar pressure distribution and gait parameters.

It includes a piezoresistive sensing matrix based on a Velostat layer for transducing applied pressure into an electric signal. Another haptic system, SoleSound, a wearable system, delivers ecological, audio-tactile, underfoot feedback to help Parkinsonian patients with the freezing of gait (FOG) issue [53].

Another common challenge that haptic systems address is the loss of sensation and range of motion in the foot–ankle complex. Lower limb prosthesis users experience this type of challenge during stair descent. Studies [54,55] addressed this challenge by providing force information through haptic feedback and restoring access to sensory information of the stair edge, whereas [56–58] used a smart insertable shoe insole, which activates a vibrotactile cue that aims to improve gait and balance control to prevent falls in patients with gait disorder.

Several haptic systems that addressed object grasping were found in the literature. For example, DextrES [59], a wearable glove that is light in weight (<8 g), attempted to address the lack of dexterity and touch feedback in virtual and augmented reality experiences. The glove used thin, flexible sensors and actuators to give users realistic touch sensations and finger movement feedback. Similarly, HaptX [60] and Meta's Haptic VR Glove Prototype used a combination of haptic feedback and force sensors to provide users with a sense of touch and resistance when interacting with virtual objects [61]. In contrast, the Hi5 VR Glove provided users with finger and hand tracking and haptic feedback, allowing them to interact with virtual objects and environments more naturally [62].

Haptic systems have also been used to help users gain a sense of the terrain. For instance, ref. [63] described a bladder-based smart shoe with a biomechanical response demonstrating the haptic rendering of subtle terrain features and compensating for uneven terrain. Similarly, RealWalk [64] is a pair of haptic shoes that was designed to create realistic sensations of ground surface deformation and texture using Magnetorheological (MR) fluid. Another study [65] also presented an MR actuator that can be easily inserted into haptic shoes and can haptically simulate the material properties of the ground. In comparison, Taclim [66] is a commercial haptic solution that provides the feeling of wearing shoes in a VR environment or walking on different types of ground, including desert or grassland, or with water on the soles of the feet.

Several haptic systems have recently emerged to improve the sense of touch in a VR or AR environment. Avatar VR [67], Sensorial XR [68], Tactical Haptics (Reactive Grip) [69], and Manus Polygon (PRIME X) [70] have attempted to provide realistic and immersive haptic feedback in virtual and augmented reality experiences. Various sensors and actuators focus on providing more detailed and precise feedback to the hands and fingers. The common goal of these haptic systems is to enhance the overall sense of presence and realism in virtual environments, making the experience more engaging and believable for users. By providing more realistic haptic feedback, users can interact with virtual objects and environments more naturally and intuitively, creating a more seamless and immersive experience.

Commercially, Haptic Workstation by CyberGlove Systems provides users with a realistic and immersive virtual reality experience. It is a fully integrated simulation system that provides right and left whole-hand haptic feedback, immersive 3D viewing, and easy-to-use CAD model manipulation and interaction software [71]. Haptic workstations can save the cost of prototyping the devices.

Haptics systems have also been used to assist the hearing-impaired community to uniquely experience gaming and music. DropLaps [72] technology converts audio into vibrations that can be felt from the feet throughout the entire body, thereby transforming music, movies, and games into immersive, live experiences.

5.2. What Haptic Technologies Have Been Used and in What Contexts?

Haptic feedback devices have been used to convey subtle informational cues to users. These come in two basic categories: kinesthetic and tactile. Kinesthetic haptic feedback utilizes mechanical forces to provide feedback to the user [73]. Tactile haptic feedback uses purely sensory cues, such as vibrations, to inform the user of events or provide the illusion of forces [17], such as the system presented in [11], a wearable system that applies vibrotactile cues to the feet and visual cues through augmented reality glasses to convey obstacle location and proximity.

There are a variety of actuation technologies that can be used to generate haptic feedback. Table 2 shows an overview of the haptic types and actuators. Mechanical actuators use a source of power to achieve physical movement. Mechanical actuators can be found on nearly every automated machine. The three main types of actuators are pneumatic (air pressure), hydraulic (fluid pressure), and electric [12]. An example of mechanical actuators is the pair of kinesthetic shoes found in [63] that uses pneumatic actuators to allow the smart shoe to operate passively by opening selected valves based on the height profiles controlled by the desired terrain features. This allows the corresponding bladders to deflate as the user steps on the shoe and to reinflate when they lift their foot during the swing phase of gait.

Other actuators are electromechanical (EM), which use electric and mechanical forces to generate haptics. For example, Exoskin, a haptic system for the fingertips of a glove [10], can selectively transmit haptic information from the outside of the suit to the inside, i.e., onto human skin. The system consists of two layers. First, a passive mechanically actuated layer consisting of free-moving pins on a flexible material. Second, an active electrically controlled jamming layer for programmable stiffness.

Buzzing sensations are the most common feedback delivered by vibrotactile actuators [74]. Vibrotactile actuation, however, may produce far more nuanced haptic sensations, provided it is strongly related to users' activities. Several haptic systems have used vibrotactile actuators in boots for a variety of reasons. For example, in [11], vibrotactile boots apply vibrations to the front of the foot with two small haptic motors (Vibrating Mini Motor Discs) to provide obstacle location and proximity information. The study in [54] also used vibrotactile actuation by using a sensorized insole wirelessly connected to a textile waist belt with three vibrating motors. Three stimulation strategies for mapping the insole pressure data to vibrotactile feedback were implemented and tested during level and stair walking. In [53], the haptic system consisted of two footwear units and a belt unit. Pressure under the foot and kinematic data of the foot are sent wirelessly to a portable single-board computer attached to the belt. The audio-tactile feedback is generated in real time and converted to analog signals by a sound card. Thin stereo audio cables carry the analog signals from the waist to each foot, which are then amplified and fed to vibrotactile transducers and loudspeakers. Similarly, ref. [55] designed a custom insole with four force sensors and a thigh band with four vibrotactile actuators to provide force information through haptic feedback. The feedback can assist lower limb prosthesis users during stair descent. A study [75] used vibrotactile feedback in the insole to warn the user to correct their posture using their muscles.

Other vibrotactile actuators have been used in haptic systems to support individuals with hearing impairments. For instance, the system in [76] used vibration feedback with a touch interface to give users additional confirmation that the device received their input. This system is useful for deaf individuals or those unfamiliar with touch interfaces.

Vibrotactile actuators have also been used to help users with object grasping. For example, Reactive Grip [69] touch feedback works by mimicking the friction forces experienced by users as if they were really grasping the object in the virtual environment with which they are interacting. These friction forces are applied through the motion of actuated sliding plate contactors (also called "tactors") that move on the surface of the device's handle. The device can provide force/torque cues to users in response to their actions through the actuation of its sliding plates.

Microfluidic actuators have also been used in haptic systems for various applications. The actuators are based on flexible, biocompatible materials that can be produced using thin-film process technology [77]. The US-based company HaptX Inc. features the design of the HaptX Glove™, which resembles an armored glove, and the actuation principle is pneumatic [60]. Magnetic sensors capture finger movements with sub-millimeter motion-tracking accuracy. The HaptX Glove includes over 100 tactile actuators and delivers up to 22 N of force feedback. The HaptX Glove is intended for VR training and simulation applications for industrial users.

MR fluid actuators use magnetorheological (MR) fluid, which is a material whose rheological properties may be continually altered by the strength of an external magnetic field [78]. MR fluid actuators offer many benefits, including quick reaction times, low power consumption, and structural simplicity. However, designing a magnetic core for magnetic field generation for MR fluid actuators is necessary. A few haptic systems have used MR fluid actuators. For instance, RealWalk [64] used MR fluid actuators in shoe soles. When a user steps on the ground with the shoes, the two MR fluid actuators are pressed down, creating a variety of ground material deformations, such as snow, mud, and dry sand. Similarly, the system in [65] also used MR actuator insoles that can be easily inserted into haptic shoes and haptically simulate the material properties of the ground.

Finally, Electrical Muscle Stimulation (EMS) is a new generation of haptic systems. Rather than actuators, EMS uses electrical impulses to stimulate muscular contractions to create interactive systems [79]. EMS has three main applications: immersion [80], information access [81], and training [82]. The Tesla suit is an example of an application in the area of immersion, such as the simulation of collisions in a VR environment [83]. Several variations of the suit can be used for training and rehabilitation.

Table 2. The main types of actuators used.

Haptic Type	Actuator Type	Examples
Kinesthetics	Mechanical	Shoes [63]
Kinesthetics/Tactile	Electromechanical (EM)	Glove [10]
Tactile	Vibrotactile	Shoes [11], insole [53], insole [54], insole [55], insole [56], glove [68], glove [69], insole [75], touchscreen [76], smartwatch [84]
Tactile	Magnetorheological (MR) fluid	shoes [64], insole [65]
Tactile	Microfluidic actuators	Glove [60]
Tactile An electrotactile array	N/A	An electrotactile array on the tongue [85]
Electrical Muscle Stimulation (EMS), Transcutaneous Electrical Nerve Stimulation (TENS)	N/A	Suit [83]

Concerning the contexts of use, it was observed that most of the academic papers were used in a healthcare context to improve gait performance among PD patients and lower limb amputees [52–56,75] (Table 3). Meanwhile, other haptic systems were intended for use indoors for a variety of applications, mostly for enhancing the sense of virtual terrain [63–65]. Among the few haptic solutions used for space exploration, those in [10] aimed to help sense objects outside the spacesuit and those in [11] aimed to help sense the terrain. Studies [57,58] used commercial haptics that focused on gait analysis.

Table 3. Contexts of use for academic haptic systems.

Context of Use	Haptic Type	Example Applications and References
Indoors	Kinesthetics	Shoes [63,65]
Indoors	Tactile	Shoes [64], gloves [59], touchscreen [86]
Space	Tactile	Gloves [10], shoes [11]
Healthcare	Tactile	Shoe insole [52], shoe insole and vibrotactile belt [53,54], an electrotactile array on the tongue [85], shoe insole and thigh belt [55], shoe insole [56,75]

On the other hand, most commercial haptic systems have been designed for indoor use, such as gaming, VR training, and simulation applications [60–62,67–69,71,72,83], mostly to help users with a sense of touch and virtual terrain, as well as grasping objects (Table 4). Only a few commercial systems have been designed for healthcare applications such as [57,58] to assist with gait analysis and performance.

Table 4. Contexts of use for commercial haptic systems.

Context of Use	Haptic Type	Example Applications and References
Indoors	Tactile	Shoes [18,72], gloves [60–62,67,70], touch interface [76], gaming equipment [69]
Indoors	EMS	Gaming suit [83]
Healthcare	Kinesthetics	Shoe insole [57]
Healthcare	Tactile	Shoe insole [58]
Training	Tactile	Glove exoskeleton [71], glove [68]

5.3. What Are the Approaches to the Haptic Solutions?

Common approaches to haptic solutions include vibration motors, piezoelectric actuators, electrostatic or electromagnetic actuators, and hydraulic or pneumatic systems. In [63], the smart shoe's design was based on the haptic rendering of gross features such as small slopes and subtle terrain elements such as subfoot-sized objects. The smart shoe is deflated to simulate small slopes, resulting in foot inversion/eversion (roll) and dorsiflexion/plantar flexion (pitch). The key haptic feedback is the smart shoe is deflated to simulate small slope displacement variations generated by the terrain rendering. This makes the shoes appropriate for application in PD gait training.

The RealWalk shoe uses two MR fluid actuators, an insole pressure sensor, and a foot position tracker. By changing the magnetic field intensity in the MR fluid actuators based on the ground material in the virtual scene, the viscosity of the MR fluid is changed accordingly [64]. The RealWalk design feasibly supports the use of s to enable VR applications and opens many possibilities.

The SoleSound shoe sole [53] primarily targets clinical applications. It uses an audio-tactile footstep synthesis engine informed by pressure readings and inertial sensors embedded in the footwear to integrate enhanced feedback modalities into the authors' previously developed instrumented footwear. Another insole designed by [55] has four force sensors, a thigh band with four vibrotactile actuators, and an onboard embedded processor. Providing force information through haptic feedback assists stair descent for users of lower limb prostheses. A study [56] also used vibrating motors as haptic feedback for gait disorder or losing functional autonomy. The risk computed is associated with the appropriate rhythmic cueing to improve balance and gait impairment.

The ExoSkin glove prototype uses a two-layer approach for haptic feedback. The mechanical layer comprises flexible fabric with plastic pins to transfer shape and lateral deformation. The electronic layer involves a silicone bladder containing coffee grains and a peristaltic pump to control the amount of air and flexibility [10]. In [59], an electrically controlled friction force was generated based on an electrostatic clutch generating up to 20 N of holding force on each finger by modulating the electrostatic attraction between flexible elastic metal strips. Cutaneous feedback is provided via piezo actuators at the fingertips. A study [61] demonstrated VR grasping using 15 ridged and inflatable plastic pads known as actuators. The pads are arranged to fit along the wearer's palm, the underside of their fingers, and fingertips. Soft actuators and the "world's first high-speed microfluidic processor," a chip that controls the glove's airflow system, power the actuators.

5.4. What Are the Reported Limitations of Existing Haptic Systems?

Academic attempts have reported several limitations, but we could not find any limitations for the commercial haptic systems as the manufacturers did not report them.

For example, concerning shoes, in [63], the smart shoe rendering varied between subjects and could be made more consistent by implementing feedback control, improving subject training, and assuring consistent gait speed. Feedback control could also provide variable impedance terrain display for rendering softer and harder terrain. In another study aimed at space shoes [11], participants differed in their cue perception capabilities of the haptics. Furthermore, participants had limited exposure to the display technology and were required to learn how to utilize the information cues quickly. As such, the authors concluded that the participants may have benefited from more extensive training and experience with the system. In the context of healthcare, the authors of [54] stated that their haptic system embedded in shoe insoles lacked the validation of the results with lower limb amputees to test the effectiveness of the wearable haptic feedback system and the CoP-based strategies in improving users' gait performance (e.g., temporal symmetry, speed, cognitive workload) during ground and stair-walking tasks. As such, the authors plan to test a neuromorphic strategy on different terrains to verify the possibility of conveying different terrain features, with the final goal of improving amputees' contextual awareness. In the context of VR, ref. [64] reported that haptic shoes were heavy, bulky, and tall, making it difficult to walk around. The shoes also consumed high power. Furthermore, the study mentioned that some ground materials were challenging to simulate because of the equipment's inherent viscosity limitations. The authors also stated that adding an active vibrotactile actuator to an MR fluid actuator could maximize performance. Two other studies reported on the limitations of their haptic shoe attempts in a healthcare context, including a small sample size used for testing [53] and the difficulty in measuring the performance of the shoes due to the variety of gaits and balance strategies [55].

Finally, ref. [10] reported on a limitation of their spacesuit gloves. The prototype was implemented on the fingertips only, although it can be extended to the whole hand and other body parts (e.g., arms or feet). Further investigations are needed to create higher-fidelity prototypes and evaluate their usefulness for specific tasks.

5.5. What Evidence Exists to Support the Validity of Haptic Systems?

The authors of the surveyed haptic systems mainly conducted two types of evaluations, qualitative and quantitative, to substantiate the validity of the haptic systems. The qualitative evaluations relied on participants' opinions and perceptions of the haptic systems, whereas the quantitative evaluations reported the factual data collected from experimentation using the haptic systems.

Table 5 shows an overview of the qualitative evaluations carried out to substantiate the surveyed haptic systems. In general, the evaluations measured the participants' experience with the haptic systems in terms of general experience [10], comfort and intuitiveness [54], mental and physical performance [86], and how realistic the sense of touch was [85]. The number of participants tended to be low (at most 16) and the results pointed to mixed findings. The study in [11] did not find any evidence to support the haptic system, possibly because it was the first haptic exposure for participants. In other instances (e.g., [85]), the haptic system was a positive experience for the participants.

Table 6 shows an overview of the quantitative evaluations carried out to validate the surveyed haptic systems. In general, the evaluations measured the identification of the surface details [63], accuracy of learning [84], position identification [55], longevity of the haptic system [63], task completion time and collision count [11], gait pattern [53], and falling risks [56]. The results mostly suggested a positive influence on haptic systems in terms of the surface identification, position identification accuracy, obstacle avoidance, and gait improvement. However, haptic systems also resulted in worse task performance [84] and longer completion times [11]. Nonetheless, one study [55] showed that when a haptic experiment was repeated, the participants tended to perform better in various tasks.

Table 5. An overview of the qualitative evaluation conducted to assess the haptic systems.

Evaluation Type	Metric Measured	No. of Participants	Findings	Reference
Interviews	EVA experience and reflections on the sense of touch and haptics	6	There was a need for varied resolutions of touch in different scenarios.	[10]
NASA Task Load	Workload ranking based on mental, physical, temporal, performance, effort, and frustration	16	Tactile-only display induced higher mental and temporal workloads compared to having no display.	[11]
Experiment (Elo rating)	Intuitiveness and comfort of shoe haptics for stair walking (different simulation strategies)	6	The intuitiveness and comfort scores were higher for two strategies: (1) center of pressure (CoP), (2) vertical ground reaction force (vGRF).	[54]
Evaluation Study	The perception of how realistic the ground was when wearing haptic shoes (MR fluid-based vs. vibrotactile)	12	Participants had a more positive experience with MR fluid-based shoes.	[64]

Table 6. An overview of the quantitative evaluation of the surveyed haptic systems.

Evaluation Type	Metric Measured	No. of Participants	Findings	Reference
Evaluation study	Participants' identification of the surface details	8	The correct identification of surface details was achieved with 93.1% accuracy.	[63]
Experiment	1. Participant's ability to differentiate distinct vibration positions on the thigh. 2. Participant's ability to indicate the staircase edge position.	15 + 13	1. The participants correctly distinguished the vibration position with a minimum accuracy of 82%. 2. The participants demonstrated increased accuracy in localizing the step edge when haptic feedback was present.	[55]
Evaluation study	Accuracy of learning Morse code using a haptic-based smartwatch	6	Lower learning scores for students using the haptic system.	[84]
Cycle life tests	The longevity of the haptics in the shoes	N/A	Compositing bladders in the shoes demonstrated more than the targeted 120 k cycles, and catastrophic structural failure did not occur.	[63]
Evaluation study	Task completion time, number of collisions	16	- Tactical haptics in shoes increased completion time by 49%. - Participants wearing haptic shoes avoided more obstacles	[11]
Evaluation Study	Gait pattern when audio-tactile haptic feedback is provided	3	Ecological underfoot audio-tactile feedback may significantly alter the natural gait cycle of young healthy subjects. The aggregate material is effective in impacting the user's gait, especially in the variables' step length and normalized swing period.	[53]
Evaluation Study	Timed Up and Go (TUG) time and risk of falling	12	Participants wearing haptic shoe insoles had a higher TUG and fewer risks of falling	[56]

6. Discussion and Implications for Haptics in Space

6.1. Discussion

This study reviewed academic and commercial haptic systems to draw inspiration for the application of haptics in spacesuits.

RQ1 reviewed the problems that haptic systems have addressed. It was observed that haptic systems have been used to address various problems, including gait analysis and monitoring and the simulation of a sense of grasping, touch, and virtual terrain. Many of these problems, e.g., the need for a sense of terrain and touch, are faced by astronauts in space exploration.

RQ2 reviewed the types of haptics and the contexts in which they were used. We found that various types of haptics have been used, including kinesthetic and tactile, with various actuator types, including mechanical, electromechanical, and vibrotactile. Academic and commercial haptic systems have been used in several contexts, including indoors and in medical environments. Electrical Muscle Stimulation (EMS) and Transcutaneous Electrical Nerve Stimulation (TENS), two emerging haptic systems, have been used commercially in gaming suits, whereas haptics has been used in spacesuits as tactile actuators in gloves and shoe insoles.

RQ3 reviewed the approaches to haptic systems. We found that haptic solutions for wearable devices included various actuators such as vibration motors, piezoelectric, electrostatic or electromagnetic, and hydraulic or pneumatic systems. Prominent examples included shoes that used deflation to simulate small slopes and terrain elements or shoes that used MR fluid actuators to change viscosity based on virtual ground materials. Other shoes provided audio-tactile footstep feedback or force sensors and vibrotactile actuators for gait assistance. Some gloves used mechanical and electronic layers for haptic feedback, whereas others use ridged and inflatable plastic pads with microfluidic processors to control airflow.

RQ4 reviewed the limitations of the existing haptic systems. It was observed that some academic studies have reported on the limitations of haptic systems for wearable devices, but the limitations of commercial systems are not well-documented. Examples of the limitations reported for haptic smart shoes included that the perception can vary between subjects and require feedback control for consistent rendering, as space shoes can be heavy and consume high power. In healthcare contexts, haptic insoles lacked validation with amputees, whereas haptic shoes faced limitations due to small sample sizes and difficulties in measuring performance. A study on spacesuit gloves found some limitations in their prototype, which was implemented only at the fingertips and required further investigation of higher-fidelity prototypes.

RQ5 examined the evaluation methods used to assess the effectiveness of haptic systems. The authors of the surveyed haptic systems conducted qualitative and quantitative evaluations to substantiate the validity of the systems. The qualitative evaluations measured participants' experience in terms of comfort, intuitiveness, and the realism of touch, whereas the quantitative evaluations measured the surface and position identification accuracy, obstacle avoidance, and gait improvement. The number of participants was generally low and the results were mixed, with some studies showing positive experiences and influences on haptic systems, and others having negative influences on task performance and completion time. However, repeated experiments showed improved performance in various tasks.

6.2. Implications for Haptics in Space

6.2.1. Haptic Systems Key Metrics of Importance

To shed light on the metrics considered when designing haptic systems, we collected the surveyed haptic systems' weight, power, frequency, response time, and voltage to understand how the systems fare across these metrics. We could only collect this information for a few haptic systems as it was not readily available for the other systems. For spacesuit design, the ideal haptic system will have a low response time, weight, and power consumption, and a high frequency.

Figure 3 shows the device weight versus the power consumption. The relationship between the weight and power looks positive. The heavier the weight, the higher the power consumption. The figure shows the vibrotactile haptics used in the VR glove that featured the lowest weight and power consumption [59], whereas MR fluid haptics used in a shoe [64] and kinesthetic haptics [57] used in shoe insoles exhibited a higher weight and power consumption.

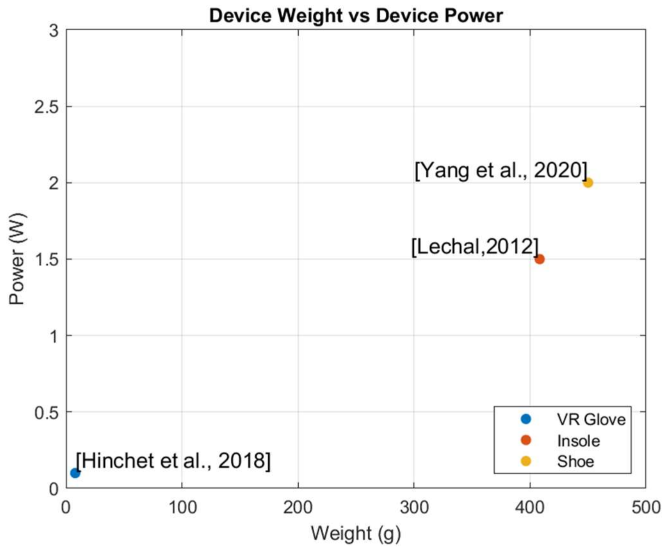

Figure 3. A scatter plot showing the weight of the haptic system against the power consumption [57,59,64].

Figure 4 shows the response time versus the motor voltage. The relationship between the two variables is mostly positive, except for the haptic glove used for the VR [70]. The higher the voltage, the higher the response time. Ideally, a low response time and voltage are desirable for space haptics. The figure shows the vibrotactile haptics used in the VR glove that featured the lowest response time and voltage [55]. The system used vibrotactile actuators to assist lower limb prosthesis users during stair descent.

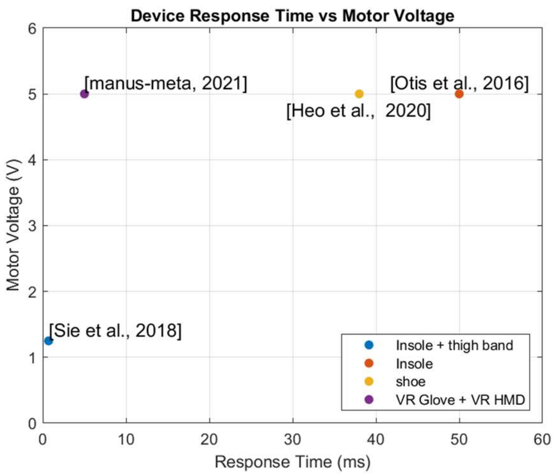

Figure 4. A scatter plot showing the response time of the haptic system against the motor voltage [55,56,65,70].

The haptics shown in the graph with a higher voltage and time response used an MR actuator to simulate the material properties of the ground [65], whereas the other study featured a haptic system that used vibrotactile haptics in a shoe insole [56].

Figure 5 shows the response time versus the frequency of the motor. The relationship between the two variables appears to be negative. The lower the frequency, the higher the response time. Ideally, a low response time and high frequency are desirable for space haptics. The figure shows that the vibrotactile haptics used in the VR gloves had the lowest response time and highest frequency [55].

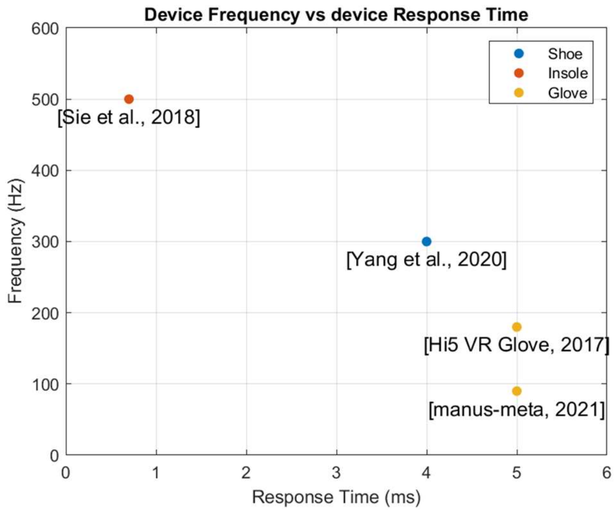

Figure 5. A scatter plot showing the response time of the haptic system against the motor voltage [55,62,64,70].

In contrast, other vibrotactile haptic gloves [62] offered a higher response time and lower frequency, whereas MR fluid haptics used in a shoe [64] offered a lower response time and higher frequency.

The haptics that we collected information on in this section were largely vibrotactile, MR fluid, or kinesthetic haptics. However, compared to traditional haptics, the relatively recent yet overlooked type of haptics based on direct nerve stimulation (Transcutaneous Electrical Nerve Stimulation) could offer an attractive trade-off. This variant trades lower haptic fidelity (frequency) for simplicity, a low weight, and power consumption.

Figure 6 shows a box and whisker chart illustrating the distribution of retail prices for different commercial haptic products. The median is shown as a horizontal line within the box. Outliers are data points outside the whiskers and are plotted as individual points. This chart shows that the retail prices for the full-body suit have the largest range and the highest median price, whereas the retail prices for shoes have a relatively smaller range and lower median prices. The VR Glove and HMD and AR/VR have similar median prices, but the VR Glove and HMD has more variability in retail price. The glove has a moderate range and a median price.

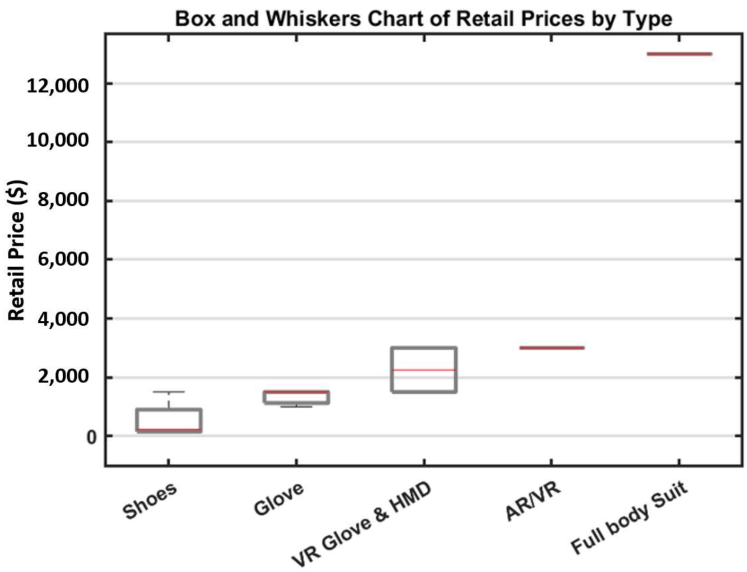

Figure 6. A box and whisker plot showing the retail price of the commercial haptics solutions.

6.2.2. Safer Walking on Mars/Moon

Astronauts are shielded from their surrounding environment by the spacesuit, particularly the spacesuit footwear. By understanding the astronauts' sensory needs during extra-vehicular activities (EVAs), haptic footwear can be developed to emulate the terrain. Due to the lack of assistance from gravity, walking in space is substantially more exhausting than walking on Earth. For instance, MIT has tested haptic feedback on footwear that vibrates to alert the user to their proximity to an antenna or an invisible rock while walking on soil. This simulated Martian environment gives astronauts a more realistic simulation of weightlessness and their surrounding area. They can also avoid injury due to uneven terrain while exploring another planet. Haptic footwear helps astronauts avoid injuries caused by uneven terrain and extraterrestrial objects on the Martian surface [11]. Moreover, haptic shoes provide the next level of physical realism for VR games and movies and can provide users with realistic sensations to simulate walking on a surface with its gravitational force. One study presented a pair of haptic shoes for HMD-based VR that were designed to create realistic sensations of ground surface deformation and texture using Magnetorheological fluid (MR fluid). Realwalk generates realistic ground surface deformations and texture sensations for four VR scenes: grass, sand, mud, and snow [64]. Other research studies [63] used mechatronics to achieve haptic terrain. New bladder models, which include wall mechanics and air behavior, enable parametric shoe simulations to examine design factors, loading situations, and user sizes. The bladder-based soft robotic smart shoe can render subtle features and slopes.

Furthermore, haptic simulation can also be achieved through nerve-tactile communication, as illustrated in [83]. SmartTouch converts the visual pictures the sensor has acquired through electrical stimulation into tactile information. The technique enables it to recognize printed materials through touch. Additionally, Tacttoo [87] is a temporary electro-tactile interface developed and constructed so that mechanical penetration of the gadget by natural tactile stimuli is possible without user input. This is comparable to a see-through optical display in the visual modality; this class is referred to as a passive feel-through class.

6.2.3. How Can Spacesuits/Haptic Solutions Reduce Cognitive Load/Sensory Deprivation/Low Pressure/High-Pitch Sound?

The auditory channel has the potential to be highly loaded during EVA operations due to radio communication protocols so the addition of tactile cues may be a more appropriate design choice in this operational scenario. Elliott et al. [88] pointed out that many studies have demonstrated success with tactile cues for waypoint land navigation, especially during low-visibility conditions or when attention is focused on surrounding ground terrain. In 2019, the benefits of touch response in space were further studied from a physiological perspective, suggesting that sensory feedback may support psychological and social well-being, heightening experiences and promoting occupational safety [2].

There is extensive research in the area of haptic feedback for VR applications [89]. Son et al. [90] designed and tested haptic shoes to create realistic sensations of ground surface deformations and textures through MR fluid actuators while walking in VR. When a user steps on the ground with the shoes, the two MR fluid actuators in each shoe are depressed, creating a variety of ground material deformations, such as snow, mud, and dry sand, by changing the viscosity. Compared to vibrotactile-haptic shoes, the study found that MR fluid actuator haptic shoes achieve higher ratings in terms of discrimination, realism, and satisfaction. Gilded gait [91] is another type of haptic shoe that changes the ground's texture using vibrotactile feedback. Sie et al. [55] demonstrated the feasibility of haptic feedback to sense the step's edge without a visual aid. The study designed a custom insole with four force sensors, a thigh band with four vibrotactile actuators, and an onboard embedded processor. The identified haptic solutions either created a realistic sensation of the ground (terrain) or provided cues for obstacle avoidance and edge sensing (e.g., stairs), but both solutions were not consolidated in a single design.

Gibson et al. [11] conducted a study using a wearable system that applied vibrotactile cues to the feet and visual cues through augmented reality glasses to convey obstacle location and proximity. NASA TLX workload scores suggest that the tactile-only display induced higher mental and temporal workloads than no display. Displays with tactile cues had more head-down and longer completion times than visual displays. This could have resulted from increased mental processing time, perceptual limitations/ambiguities of vibrations during walking, and/or cue comprehension confidence.

Seah et al. [10] identified two main design requirements to enhance haptic feedback through a glove: (i) transfer of the shape and pressure features of haptic information, and (ii) management of the amount of haptic information. The study identified that there is a need to enhance haptic feedback when wearing gloves and also to reduce haptic feedback for certain tasks to improve an EVA experience.

6.2.4. How Can Haptic Space Footwear Be Evaluated for Safety and Accuracy?

Spacesuits are not created for physical comfort so mass amounts of work in partial gravity are difficult. Mars has approximately twice as much gravity as the Moon and the Martian terrain is far less forgiving. An unanticipated fall could puncture or damage critical life-support equipment, risking astronaut safety and mission timelines [92]. One study presented a wearable multimodal interface system to examine human performance when visual, vibratory, and visual-vibratory cues were provided to aid in ground obstacle avoidance with limitations similar to what astronauts on an EVA may encounter (reduced peripheral vision and proprioceptive feedback). The wearable system applies vibrotactile cues to the feet and visual cues through augmented reality glasses to convey obstacle location and proximity. Participants performed an overground obstacle avoidance task with the multimodal device. A ten-camera motion capture system was used to capture human kinematics. Performance metrics included the completion time, subjective workload, head-down time, collisions, and gait parameters. After each display type set of trials, participants completed a NASA Task Load Index (TLX) survey. They ranked the workload of the preceding trials based on six types: mental, physical, temporal, performance, effort, and frustration. Participants also rated the intuitiveness of the visual and tactile cues at the end of the experiment. The results indicated that information displays enhance task performance, with the visual-only display promoting the least head-down time over tactile-only or visual-tactile displays. Head-down time was the highest for trials without a display [11]. One study [27] presented the requirements and preliminary system architecture for a wearable sensor suit system, referred to as the Injury Monitoring System (IMS), which was capable of quantifying the kinematics and dynamics of human–spacesuit interactions almost throughout the entire body. The pressure sensors were specified to measure pressure in a range physiologically relevant to pain. The contact pressure profiles can identify the spatial and temporal locations where contact with the suit may result in pain. When combined with temperature and humidity measurements on the same areas of the body, this information can be used to assess which locations on the wearer’s body have a high relative risk of injury while working in the suit. To test the garment’s comfort, a modified Corlett–Bishop discomfort scale is used; the mobility is assessed according to the Cooper–Harper Body Control scale.

6.2.5. What Haptic Technology Is Useful for Space Exploration?

A vital piece of information about the system that the user interacts with is transmitted through an embedded physical experience that is made possible by haptic feedback technology, which enables users to receive information through their bodies.

1. Haptic suit:

These technologies can be applied to the creation of virtual objects in computer simulations, the control of such items, as well as the improvement of the remote control of the machinery and gadgets. TESLASUIT [93] is one of the leading companies that provides haptic sensation for VR/AR players and is currently working on the Mars exploration project

"E.VA project", which is dedicated to supporting astronauts during space exploration. The main concept behind E.VA is to provide a virtual environment with an interactive user interface so that astronauts may engage in various interesting Earth-based activities in a high-fidelity virtual environment. Astronauts can physically experience the virtual world due to haptic sensor technology, another significant component of E.VA. Therefore, the E.VA solution will minimize psychological stress and aid in stimulating muscles when weightless.

2. Rover robot:

A paper by the European Space Agency (ESA) [94] presented experiment ANALOG-1, where the astronaut Luca Parmitano used a robotic arm to operate a ground-based rover fitted with a sophisticated gripper, which has the same mobility and dexterity as a human hand while orbiting the Earth at an 8 km/s speed from the International Space Station. From a mock-lunar environment, the gripper could pick up and collect sample rocks while being controlled by Luca using a 'force-feedback' joystick back in the ISS. Astronauts in orbit will soon be able to explore the lunar surface or other planets using robots rather than putting their lives in danger due to the extraterrestrial environment.

3. Haptic glove:

ExoSkin is a morphing haptic feedback layer that improves spacesuit gloves by regulating how haptic information from the outside environment is transferred to astronauts' skin. A study [10] presented the findings of a two-week field study conducted at the Mars Desert Research Station, where teams carried out missions simulating trips to Mars. To guide the design of a haptic glove, we used approaches (a haptic logbook, technological probes, and interviews) to look at user demands for haptic feedback in EVAs. Our observations contradicted the idea that haptic technology should always send as much information as possible and instead indicated that it should provide a manageable transmission. Based on these results, we determined that (i) the transmission of the shape and pressure elements of haptic information, and (ii) the management of the amount of haptic information were the two key design criteria needed to increase haptic feedback through the use of a glove.

4. Exoskeleton Controller:

Moreover, the European Space Agency (ESA) [95] introduced the Space Exoskeleton Controller (SPOC), a fully actuated haptic feedback device that performs bilateral teleoperations using eight actuated joints with a four-channel control architecture. It aims to develop a completely space-certified system so that the device may be flown to the ISS and used in future human-robotic exploration missions. In addition, in 2014, the ESA launched Haptics-1 Kit, marking the first haptic primary device to enter the ISS. A single DOF high-resolution force control joystick was sent to the ISS to investigate the effects of microgravity on kinesthetic proprioception and human motor control for the first time.

Furthermore, in [96], an innovative haptic-based teleoperation method for controlling a large-sized slave robot for space exploration was presented. This method used two specially designed haptic joysticks, a hybrid master–slave motion-mapping technique, and a haptic feedback model that rendered the operating resistance and the interactive feedback on the slave side. This research aims to control the position and orientation of a large-sized slave robot by using a user's two hands. A virtual environment simulating the slave side is run to verify the effectiveness and efficiency of the proposed solution.

6.3. Study Limitations

This research may have been affected by the following factors: (1) Our study included research articles and commercial applications published between January 2012 and December 2022. The authors needed this constraint to analyze the selected publications and commercial systems. Hence, the research may have overlooked critical publications released after this period. (2) To find academic haptic systems, we searched Google Scholar, IEEE Xplore, Springer Link, and Science Direct. To find commercial haptic systems, we searched using the Google search engine. As such, we may have overlooked important publications in other search libraries and search engines. (3) This study is not a systematic literature review; hence, we did not use a consistent search query to find academic and commercial haptic systems. As such, we may have missed some influential haptic systems. (4) The researchers may have misclassified articles. To ensure appropriate categorization, we cross-checked each author's work. At research meetings, authors cleared any doubts. (5) We may have been biased toward important technical reports or publications without sufficient empirical data while reviewing and eliminating articles.

7. Conclusions

Haptic technology reduces the sensory deprivation effect and can potentially improve astronauts' safety when interacting with their environment during extravehicular activities (EVAs). This technology, which uses touch to relay information, has been previously applied in gaming and healthcare. However, its use has never been tested in EVA spacesuits. One reason is the extreme engineering trade-offs involved in designing and producing spacesuits. In addition, there is a conspicuous need to improve current spacesuits. Current spacesuits have a low ergonomic performance record, leading to a high rate of musculoskeletal injuries.

To address this, we have provided a non-systematic overview of recent research on how haptic technology can be applied to improve future spacesuits. This study found that kinesthetics, electromechanical, vibrotactile, and MR fluid haptics and actuators have been used in indoor and outdoor settings, and various academic and commercial haptic devices have been utilized. The surveyed haptic systems have been validated by qualitative and quantitative evaluations. The quantitative evaluations examined the surface and location detection accuracy, obstacle avoidance, and gait improvement, whereas the qualitative evaluations rated the comfort, intuitiveness, and realism of touch.

We note that various studies demonstrated the usefulness of haptic technology for EVA spacesuits, including gloves, shoes, exoskeleton controllers, and haptic-based teleoperation methods. We also presented various tests, e.g., NASA Task Load, that were used to verify the safety of haptic shoes.

Finally, we showed how a few surveyed haptic systems differed in terms of weight, power, frequency, response time, and voltage, as these are crucial metrics for haptics in space. This study showed that vibrotactile haptics offer lower power consumption, voltage, response time, and frequency. However, compared to traditional vibration-based haptics, a relatively recent and overlooked variant of haptics based on direct nerve stimulation (Transcutaneous Electrical Nerve Stimulation (TENS)) could offer an attractive trade-off. This variant offers a trade-off between lower haptic fidelity and the benefits of simplicity, lightness, and reduced power consumption. Further research is needed to quantify the benefits and trade-offs of haptics for EVA spacesuits.

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Appendix A

Table A1. The selected haptic systems referred to in this study.

ID	Haptic System Author	Type	Reference
A1	Wang and Minor, 2018	Academic	[63]
A2	Seah et al., 2015	Academic	[10]
A3	Gibson et al., 2018	Academic	[11]
A4	de Fazio et al., 2021	Academic	[52]
A5	Cesini et al., 2020	Academic	[54]
A6	Shull and Damian, 2015	Academic	[85]
A7	Shen et al., 2018	Academic	[27]
A8	Yang et al., 2020	Academic	[64]
A9	Zanotto et al., 2014	Academic	[53]
A10	Sie et al., 2018	Academic	[55]
A11	Seim et al., 2018	Academic	[84]
A12	Otis et al., 2016	Academic	[56]
A13	Berengueres et al., 2014	Academic	[75]
A14	Hinchet et al., 2018	Academic	[59]
A15	İşleyen et al., 2019	Academic	[86]
A16	Heo et al., 2020	Academic	[65]
A17	Bakke and Sue, 2019	Academic	[2]
A18	Taclim, 2023	Commercial	[66]
A19	Goode, 2021	Commercial	[61]
A20	Droplabs, 2021	Commercial	[72]
A21	Hi5, 2023	Commercial	[62]
A22	Ti.com, 2023	Commercial	[76]
A23	Teslasuit, 2023	Commercial	[83]
A24	HaptX, 2023	Commercial	[60]
A25	Lechal, 2023	Commercial	[57]
A26	Vibrasole, 2023	Commercial	[58]
A27	Haptic Workstation, 2023	Commercial	[71]
A28	Sensorial XR, 2023	Commercial	[68]
A29	Tacticalhaptics, 2023	Commercial	[69]
A30	Manus, 2023	Commercial	[70]
A31	Avatar VR, 2023	Commercial	[67]

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