This paper appears in Progress in Biomedical Engineering, 2021.
https://doi.org/10.1088/2516-1091/abee66

# Kinematic design of linkage-based haptic interfaces for medical applications: a review

**Ali Torabi[1,3], Ali A. Nazari[2,3], Everly Conrad-Baldwin[2], Kourosh Zareinia[2,*] and Mahdi Tavakoli[1]**

[1] Department of Electrical and Computer Engineering, University of Alberta, Edmonton, AB, Canada.
[2] Department of Mechanical and Industrial Engineering, Ryerson University, Toronto, ON M5B 2K3, Canada.
[3] These authors contributed equally.
[*] Corresponding author.

E-mail: {ali.torabi, mahdi.tavakoli}@ualberta.ca, {ali.nazari, everlycb, kourosh.zareinia}@ryerson.ca

January 2021

**Abstract.** A haptic interface recreates haptic feedback from virtual environments or haptic teleoperation systems that engages the user's sense of touch. High-fidelity haptic feedback is critical to the safety and success of any interaction with human beings. Such interactions can be seen in haptic systems utilized in medical fields, such as for surgical training, robotic tele-surgery, and tele-rehabilitation, which require appropriate haptic interface design and control. In order to recreate high-fidelity soft and stiff contact experiences for the user in the intended application, different designs strike different trade-offs between the desirable characteristics of an interface, such as back-drivability, low apparent inertia and low friction for the best perception of small reflected forces, large intrinsic stiffness and force feedback capability for the best perception of large reflected forces, a large-enough workspace for exploring the remote or virtual environment, and the uniformity of haptic feedback and its adequate sensitivity over the workspace. Meeting all of the requirements simultaneously is impossible, and different application-driven compromises need to be made. This paper reviews how various kinematic designs have helped address these trade-offs in desired specifications. First, we investigate the required characteristics of linkage-based haptic interfaces and inevitable trade-offs between them. Then, we study the state of the art in the kinematic design of haptic interfaces and their advantages and limitations. In all sections, we consider the applications of the intended haptic interfaces in medical scenarios. Non-linkage-based haptic interfaces are also shortly discussed to show the broad range of haptic technologies in the area. The potentials of kinematic redundancy to address the design trade-offs are introduced. Current challenges and future directions of haptic interface designs for medical applications are shortly discussed, which is finally followed by the conclusion.

*Keywords*: haptics, haptic interface, user interface, kinematic design, evaluation, redundant haptic interface, medical applications

## 1. Introduction

Touch is the first sense that humans develop. Tactile and kinesthetic perceptions are used to understand objects' various properties, such as shape and stiffness, through the skin and muscle stimulation [1]. This combination of perceptions, known as haptic perception, provides humans with their most basic method of understanding and effecting change over an environment. A related concept, haptic feedback, can stimulate this perception for humans who operate machines to interact remotely with an environment, allowing for safe, reliable, and precise interaction [2].

To emulate touch, a haptic interface produces forces matching sensed force data received from the robotic or virtual (follower) proxy probe. A haptic teleoperation system or virtual environment (depending on whether the proxy is robotic or virtual) is created for the user to interface with the proxy to interact with the remote environment. The applied haptic feedback of the proxy's interaction with the environment gives transparent (that is, a real-feeling, high fidelity) touch stimulation to the user to emulate actual direct interaction with the environment by the user more accurately. Such systems have found use in domains that include medicine - for surgical training by use of a virtual proxy, in robotic (tele-)surgery, and in (tele-)rehabilitation via a virtual or robot proxy, as examples [2].

A haptic interface is therefore an actuated, computer-controlled, and instrumented machine that establishes a bilateral interaction between the virtual or remote environment and the operator. The property of being not just an interface for input but also a source of user feedback makes haptic feedback devices unique, and the quality of their hardware and the design of their controllers will directly alter the realism, presence, and immersion of the user in the virtual or remote environment, and therefore their ability to control the proxy's environment [3].

Giving force information to the user is meant to improve the telemanipulation experience to make the user feel as if they are themselves present in a remote environment [4]. This is often called the transparency of an interface [5]. Haptic interfaces do not stop with this; they attempt to create the illusion of telepresence by allowing users to interact with operative information via force constraints that have been generated virtually [6]. Active constraints, also called virtual fixtures [7], are software-generated force responses to user movements that are meant to encourage motion within a particular range, away from forbidden areas and/or along determined paths, allowing robotic precision to be used while leaving the human operator in control of motion occurrence and timing [4]. Haptic interfaces can also make a record of the intentions of the user along the interaction path, use this data to invoke visualization systems or preset user commands that may result in direct haptic feedback [8].

Haptic interaction began its current rate of growth in the 1990s. The cost of components has decreased over time, so new designs and differently sized haptic interfaces have become available [2]. Specialized hardware often needs to be invented or modified from other machinery in order to create haptic devices, but most haptic interface designers have not been engineers, so many haptic innovations have been spread in a fragmented literature [9].

Haptic interfaces are used for a variety of tasks. Many haptic feedback systems are used for training surgeons without risking a patient's health [10–12], also generally giving visual and acoustic feedback to emulate a procedure realistically. In the same way that a flight simulator works for pilot training, virtual operating rooms can be used for surgeon training while guaranteeing quantitative feedback so that the trainee can refine their practice before exercising the skills gained on actual patients [13, 14]. Other systems train joint lesion diagnosis or simulate endoscopies, laparoscopic, and intravascular interventions [3]. Better task performance has been shown by simulator-trained surgeons than those without such training [15, 16]. Given that patients are not placed in jeopardy in these simulations, early student training can be accomplished using these devices with better overall results [8]. Haptic devices have additionally been used for augmenting graphical user interfaces (GUIs) [17], scientific data visualization [18], enhancement of nano-manipulation systems [19], CAD/CAM [20], education and training, particularly surgical training [21], master interfaces in teleoperation [22], master interface in surgery [2,23–25], and rehabilitation [26–28]. It has been nearly thirty years since the first attempts were made to add robots to operating rooms [29]. Though still controversial [30, 31], in particular as relates to their cost-benefit value [13, 14], robotic systems are added each year to operating rooms in the interest of more positive surgical results [13,14], which arguably are highly dependent on the interface connecting the surgeon to the surgical robotic system. This fact highlights the importance of the design of haptic devices in such systems.

Different haptic devices provide sensations in different fashions. Hence, a variety of mechanical, electrical, and computational elements are needed to fulfill varying design specifications for different applications, such as surgery, education, and games, where producing useful haptic interfaces involves incorporating ideas, hardware, and interactions among experts and professionals from different areas. This incorporation has become essential considering the widespread use of virtual reality and physical computing to, for instance, digitally simulate/recreate physical objects in order to sense and respond to the world around interactive systems [9]. Thus, the design of a haptic device is crucial to its intended application. The problem left unsolved here is that the knowledge of haptic device design developed in the last decades has not been consolidated for the benefit of contemporary designers because this information has been fragmented in the areas of haptics, robotics, virtual reality, and human-computer interaction [9]. As a result, the need for a review paper on this area arises.

The contribution of this paper is filling the stated gap of research in the design of haptic interfaces by addressing the main categories of the mechanical design of haptic devices and introducing the contributing factors in each of the design classes as well as highlighting the criteria for evaluating the merits of a haptic interface from the design perspective. Moreover, a comparison table will provide the readers with a report on the most common haptic interfaces designed to date, together with some of their

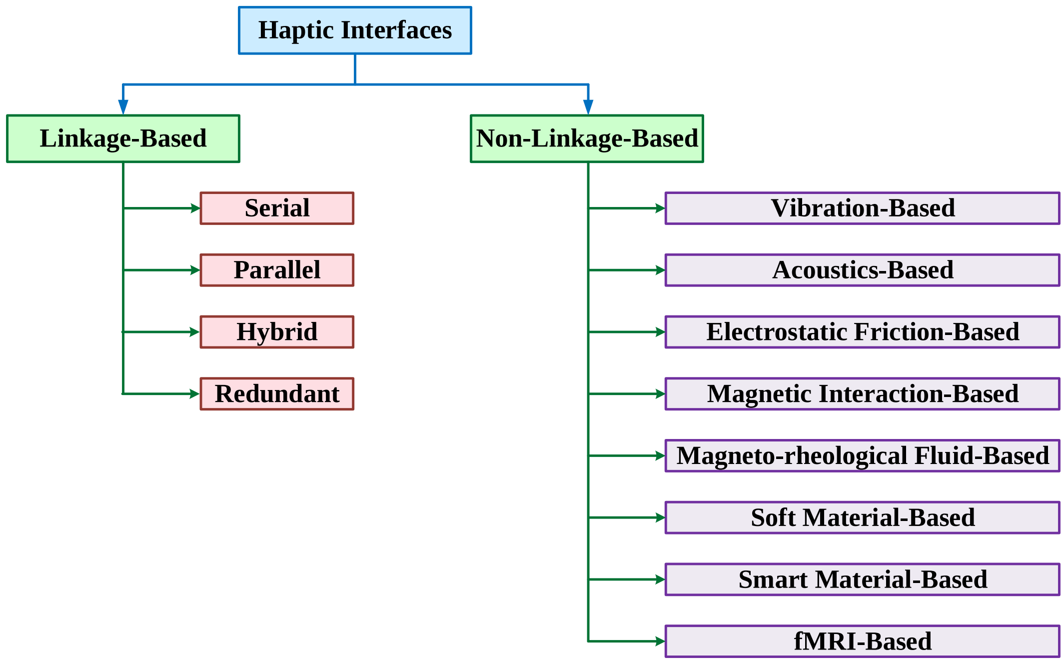



**Figure 1.** Scope of review: blocks colored in lavender represent the interfaces out of the main scope but briefly introduced in the article.

specifications.

The scope of this paper is demonstrated in Figure 1. The taxonomy of haptic interfaces can be introduced from different perspectives. This review focuses mainly on the kinematic design of linkage-based haptic interfaces. However, we briefly introduce non-linkage-based haptic devices as well to draw the attention of researchers to these fast-paced, ever-growing haptic technologies in the community. There are still other haptic devices excluded from the review due to limited space, the main scope of the review (i.e., mechanical design perspective), and review distinctions.

The structure of the paper is as follows. Section 2 opens up the avenue to the applications of haptic devices in medical areas. Section 3 states the most important design considerations of linkage-based haptic interfaces. The desired characteristics of such haptic interfaces are then discussed in Section 4. Section 5 investigates the advantages, challenges, and limitations of the main types of kinematic chains in the structure of linkage-based haptic interfaces. An overview of the methods of performance evaluation for the designed interfaces is presented in Section 6. Some future design perspectives of linkage-based haptic devices and the potentials of the redundant haptic interfaces are discussed in Section 7. Non-linkage-based haptic interfaces have also merits that are briefly introduced in Section 8. The design requirements in medical fields are shortly stated in Section 9. Section 10 provides information on the current challenges and promising future directions. Despite all technological advancements in haptic technologies, there are still challenges and promising future directions especially in medical applications which are discussed in Section 10. Section 11 finally concludes the paper.

## 2. Haptic Devices in Medical Applications

One important application of haptic devices is in the design and development of surgical simulators for operations like stitching, palpation, dental procedures, endoscopy, laparoscopy, and orthopedics [32]. For example, a surgical simulator for training, called SatureHap, was designed and developed using Phantom Omni or Touch haptic device [33]. A popular medical simulation system was discussed for the dental training system, as well as the development of an oral implantation simulator that can store data collected from trainees and to be potentially used for rehearsal and medical education [33]. Haptics technology has a growing importance in surgical operations, especially minimally invasive surgery (MIS) that is commonly used in conjunction with a robotic manipulator in a bilateral teleoperation surgical system [34, 35]. In some systems, an industrial robotic arm was used in a teleoperation system for MIS that was a modified six-degrees-of-freedom (6-DOFs) Denso VP-6242G with a serial mechanism and a PHANToM Premium 1.0 kinesthetic haptic device. In this system, the serial manipulator was employed as the follower, and the haptic device as the master [36]. An adjustable, immersive, and configurable platform for optometry training simulation was proposed, involving head-mounted displays, augmented reality interfaces, and a multi-point haptic device [37]. In another platform, preoperative planning and virtual training system were developed based on force feedback. The platform involved an Omega 6 haptic device, an immersive workstation, and a CHAI3D software toolkit (a software toolkit based on C++ for haptic simulation). Using this system, the preoperative planning data are transferred, and surgical simulations are carried out by a novice surgeon for osteotomy procedures to learn and improve their surgical skills [38]. The construction of Pneumatic Artificial Muscles (PAMs) was proposed in [39]. These PAMs have flexible and inflatable membranes, exhibiting orthotropic material behavior. Being light and formed conveniently, PAMs are also of interest for rehabilitation purposes due to their functionalities as locomotion devices [39]. The importance of haptic force feedback was shown in identifying the interaction force between the surgical instrument and human organ and tissue in virtual surgery [40]. Navigation in surgery was possible with the help of tactile and force feedback between the surgical instrument and the human organ [40]. An application of Omega 7 haptic devices is in the second generation of neuroArm surgical system that uses two haptic devices to transfer the sense of touch to both hands of a surgeon. A haptic intracorporeal palpation was proposed that uses a cable-driven robotic system and includes a remote sensing strategy [41]. The platform employs teleoperated cable-driven parallel manipulator that is a new, simple, and cost-effective approach for restoring haptic sensation during the performance of intracorporeal palpation. The conducted tests showed evidence of reasonable accuracy in estimating the amount of force. In another work, the authors integrated a 7-DOF master device into the da Vinci Research Kit and conducted tissue grasping, palpation, and incision tasks using robot-assisted surgery by experienced surgeons, surgical residents, and non-surgeons [42]. Statistical analysis showed that haptic feedback improves key surgical outcomes for tasks requiring a pronounced cognitive burden for the surgeon; however, possible longer task completion times were observed. Nevertheless, these are just some examples of the usage of haptic devices in medical applications, not a comprehensive survey.

## 3. Design Considerations of Linkage-Based Haptic Interfaces

One of the highly important design considerations of haptic interfaces is the structural transparency, with the back-drivability of the system such that the user perceives only the mechanical impedance being represented or reflected rather than that of the device's structure. Therefore, all of the mass, inertia, backlash, and friction must be reduced when possible. Additional issues such as workspace and payload capacity are usually important as well, but not so much as those mentioned above. In the same way, the fidelity of force feedback is more important than positional accuracy. Moreover, some particular designs make the kinematics uncomplicated and the dynamics decoupled or nearly decoupled, which are very useful simplifications of the system for control purposes [43].

The advantages of an effective design, however, are many. For instance, it enables the perception of extremity movement and position, improves the skilled performance of tasks by typically increasing the precision and speed of execution, and allows for a safe and repeatable virtual training [28]. When dealing with teleoperation, force feedback can reduce completion time, decrease peak forces and torques, and decrease cumulative forces and torques [44–47]. These achievements are particularly useful in training because the related virtual environments can set up a context for developing a safe and repeatable practice where the intimation of realism is improved, making the transfer of skills from the virtual into reality more likely. Besides, the performance of hand-eye coordination tasks and specifically dexterous manipulations can be improved by haptic interfaces [28]. As a tool, it can warn people about critical tasks in an effective way, make a spatial frame of reference available for the user, and improve the performance of tasks that entail hand-eye coordination [28, 48]. All these capabilities make haptic feedback systems a worthwhile area of study, and hence a conceptual design space well in need of mapping through surveys such as this one.

It is useful to evaluate a haptic interface through quantitative and qualitative measures of realistic rendering, performance, and enhancement, where the performance can be thought of as a measure of how capable the interface is in rendering a large spectrum of haptic stimuli [3, 49]. In order to evaluate the quality of a haptic feedback device in connection with force and torque feedback, the preliminary requirements have been utilized to derive a group of performance indices [50–53], but requirements for performance are usually multiple and indeed at times coupled or conflicting, such as possessing large stiffness and small inertia, having low weight and large enough workspace, and incurring low cost while having high functional performance. Some performance indices based on the stated requirements are often considered as objective functions of optimization subroutines that are sought to be minimized or maximized. Many attempts have been made to date to find an optimal haptic feedback device in this way, but predicting performance normally requires analyzing and simulating heterogeneous and complex models that are computationally intensive and demands design prototyping before guaranteeing the performance [53].

## 4. Desired Characteristics of Linkage-Based Haptic Interfaces

The usual method for determining the most fundamental and mechanical properties of a haptic interface involves ascertaining their desired characteristics. Various researchers have listed and categorized the most important requirements for proper performance [3, 52, 54, 55]. No specific values, in general, have been discovered, as the properties required are usually specific to the targeted device application. However, there is an agreement among experts of the area on the desired characteristics in each application [52, 53, 56–58]. The general design criteria are as follows. Table 1 then summarizes the highlights of these criteria.

- Workspace: The workspace may indeed be the most important manipulator property in that workspaces have inherent requirements given by the specifications of the user's task. The number of DOFs, the configuration of the kinematic chain, and the shape and volume of the workspace are all very important for task execution. The freedom of movement of a manipulator defines the workspace for user task achievement, and in the case of a haptic interface, the workspace should be large enough to equate with the real space required for task success by the human arm and the attached follower device. As regard the largeness of the haptic device workspace, it should match a comfortable range for the user. A large workspace that is cumbersome or fatiguing for the user does not add to the merits of the device. For instance, small motions of a computer mouse are mapped easily to the motions of a large pointer across a large monitor. But it is harder to match the scale of the mouse motion to the displayed pointer motion. The desirable workspace size is therefore application-dependant. Keeping that in mind, if the workspace is not large enough, users might be forced to work in a much slower fashion and use clutching to move the haptic interface repeatedly to a new position and orientation (pose) without moving the follower device [53]. The accuracy of the majority of MIS systems in real surgical operations has been improved by scaling down the motion of the follower side rather than that of the master side. While the shape of the workspace is maintained, the motion scaling extends the workspace volume required for the master side by increasing the length of each link proportional to the scaling factor.
- Dexterity: The dexterity or manipulability of the interface is a measure of its capacity to apply any arbitrary force and torque and to find any arbitrary pose

**Table 1.** General criteria for linkage-based haptic interface design.

| **Criterion** | **Significance** |
|---|---|
| Workspace | Affects the task success, ease of use, and convenience of the user in task execution (application-dependent); |
| Dexterity | Affects the capacity of the interface to apply arbitrary forces and torques and find arbitrary poses within the workspace; |
| Stiffness and Maximum Force Feedback | Affects the emulation of highly stiff environments and the realistic feedback to the user; |
| Weight, Friction, and Back-drivability | Affects the impedance level of the interface; |
| Bandwidth | Affects the speed and frequency at which the interface operates at maximum. |

within the given workspace [59]. An attached important factor is the interface's isotropy, providing to what extent a haptic interface might be uniform in its motion and force production in varying directions, which full isotropy is known as directional uniformity [53].

- Stiffness and maximum force feedback: By producing large forces against the user, even despite limited joint torque, a haptic interface should emulate environments of high stiffness, else the real environment will be translated to the user in a way that they read as softer than in reality [53].
- Light weight, low friction, and back-drivability: If the follower moves within free space, the interface itself should exert no wrench on the user's hand(s), and therefore requires low impedance (mainly inertia) and low friction. In particular, this is important with high accelerational motions. The mechanical structure, configuration, and actuators of the interface will define its frictional and inertial qualities. An impedance, being the ratio of force out to motion input, contains inertia, damping, and stiffness components [53].
- Fast response (large bandwidth): Bandwidth determines the speed and frequency at which the interface may operate at maximum. This is the bandwidth of actuation for force generating capability of the haptic device. To create high enough resolution rendering of the transitions between stiff contact points and free space, as well as of various textures, the bandwidth range must be high. Interfaces are regularly designed to be lightweight, encouraging larger bandwidth [53].

The desirable qualities of an interface have large trade-offs, an example being between the maximum force feedback capability of an interface and its minimum inertia; otherwise, its workspace size traded off against the maximum stiffness it may depict. For a larger force feedback capability, large actuators must be used, which in turn increases haptic interface inertia. Large workspaces subsequently require longer links, which will decrease the interface's stiffness and increase its inertia. For this reason, haptic interfaces have to be optimized for their particular application(s) [53].

## 5. Kinematic Design of Linkage-Based Haptic Interfaces: Advantages, Challenges, and Limitations

Designing the kinematics of a haptic interface is of high importance, particularly when designing for those interfaces that provide haptic feedback predominately - as with most robotic haptic feedback interfaces. In such devices, to link the user to the actuators of the device for providing the feedback, a machine or mechanical mechanism is used. Often, a joystick-like mechanism is used by the user to provide input commands. Consequently, to provide good haptic feedback within an ergonomic design, the most important characteristic of the device becomes the design of the kinematics [8].

In the analysis of the mechanisms and machines, the base link (link number 0) is that section of the mechanism that is considered stationary. The motion of all other links and joints of the mechanism, in terms of the position, velocity, and acceleration, are all calculated with respect to the base link. In most mechanisms, the base link is connected to the rest of the mechanism with at least one joint or kinematic pair. The rest of the kinematic pairs and links form a kinematic chain connecting the base link to the end-effector of the mechanism. The most commonly used kinematic pairs are prismatic (P), revolute (R), helical (H), universal (U), spherical (S), and cylindrical (C) joints. The mechanism interacts with the task environment at its end-effector, which is usually capable of moving in the 3D space with a defined number of DOFs with respect to the base link (base frame). If the base link is located on a mobile platform, it adds extra DOFs to the system, which are usually considered separately for motion analysis to make the mathematical equation manageable. The end-effector of a haptic device is usually the point where interaction between the operator and the device takes place [8].

One way to classify mechanisms is based on the design of their kinematic chain that can be an open kinematic chain (or serial design), a closed kinematic chain (or parallel design in which there should be at least two distinct kinematic paths from the base link to the end-effector), or a combination of open and closed kinematic chains, which is called a hybrid design (a mixture of serial and parallel designs). Depending on the application, one of the suitable designs mentioned above is used for the haptic interface [60, 61]. Figure 2 depicts different structures of the haptic interfaces.

The type of kinematic pairs and actuators used in the design of a haptic device are very important aspects of the type synthesis. Revolute joints and rotary actuators usually impose less friction and have superior back-drivability than prismatic joints and linear actuators. Therefore, they are most commonly used in commercially available haptic devices [61].

While being used, the haptic device and the human operator are mechanically coupled. As a result, it is very important to match the characteristics of these two

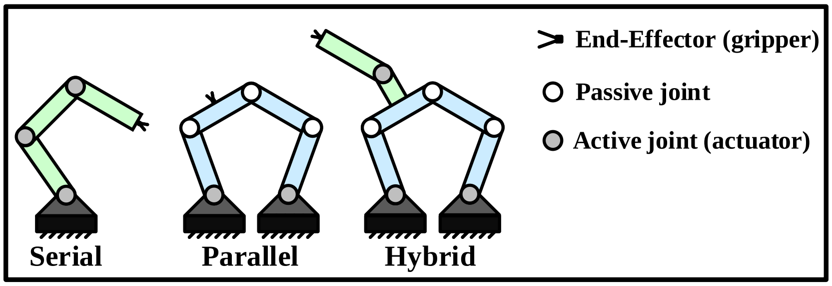



**Figure 2.** Serial, parallel, and hybrid structures.

systems, such as the size of the workspace and positional bandwidth, the magnitude of the force and force bandwidth, the velocity and acceleration, and the accuracy or the resolution of the systems [62]. This will ensure that the designed haptic interface provides a safe and effective interaction experience for the human operator that is not overqualified for the task at hand [28].

In the designing of a haptic interface, the first step is to choose the structural configuration of the system, including links, kinematic pairs, and actuators to be used in the device [8]. Depending on the application of a haptic interface or the body part with which it interacts, a suitable mechanism can be chosen. There are two types of mechanisms, serial and parallel, each of which has its own pros and cons. In serial mechanisms, a series of links are connected back-to-back, the first link is grounded, and the last link is the end-effector. This provides simplicity in design and control system; however, these mechanisms require larger motors for the same force capability. Moreover, error at the end-effector results from a combination of errors from all links and joints. In contrast, there are loops of kinematic chains in parallel mechanisms connected to the base (ground) link by two or more joints. While parallel mechanisms can provide high stiffness and precision with low inertia at the end-effector, they have a smaller workspace and are harder to control [28].

A number of haptic interfaces have been designed for a variety of applications in the last few years. These interfaces range from simple single-DOF devices [63] to complex and multi-DOF devices [64, 65]. Table 2 lists detailed specification of some of the most common haptic interfaces have been developed in the last three decades. More haptic devices can be seen in Haptipedia [9], a growing database of 105+ haptic devices have been invented since 1992. A high-DOF serial robot can have a larger workspace compared to a low-DOF robot of a similar size. The same point, however, does not remain necessarily valid for parallel robots. A haptic interface's mechanical design includes the robot's DOF determination, its kinematic mechanism, and the portability of the robot. A haptic interface's most prominent feature is the number and nature of DOFs at the active end(s), with the active end referring to the section of the robot interfacing directly with the operator's body. At this end, a hand usually holds the device, or the robot itself braces the user's body - if no such reciprocal interface exists, the interaction is considered unilateral [55]. Both active (actuated) and passive DOFs

**Table 2.** Specifications of some of the developed haptic interfaces.

| Device | Type | Workspace (mm, deg.) | DOFs of End-Effector[a] | Max. Force / Torque Feedback | Force & Torque Feedback DOFs | Ref. |
|---|---|---|---|---|---|---|
| Touch (formerly Phantom Omni) | Serial | Trans. $160 \times 120 \times 70$<br>Rot. $360, 360, 180$ | 3P + 3R | 3.3 N | 3 | [66] |
| Touch X (formerly Phantom Desktop) | Serial | Trans. $160 \times 120 \times 120$<br>Rot. $360, 360, 180$ | 3P + 3R | 7.9 N | 3 | [67] |
| Phantom Premium 1.0 | Serial | Trans. $254 \times 178 \times 127$<br>Rot. $360, 360, 360$ | 3P + 3R | 8.5 N | 3 | [68] |
| Phantom Premium 1.5 (3-DOF) | Serial | Trans. $381 \times 267 \times 191$<br>Rot. $335, 297, 260$ | 3P + 3R | 8.5 N | 3 | [68] |
| Phantom Premium 1.5 High Force (3-DOF) | Serial | Trans. $381 \times 267 \times 191$<br>Rot. $335, 297, 260$ | 3P + 3R | 37.5 N | 3 | [68] |
| Phantom Premium 1.5 (6-DOF) | Serial | Trans. $381 \times 267 \times 191$<br>Rot. $335, 297, 260$ | 3P + 3R | 8.5 N / 0.52 Nm | 6 | [68] |
| Phantom Premium 1.5 High Force (6-DOF) | Serial | Trans. $381 \times 267 \times 191$<br>Rot. $335, 297, 260$ | 3P + 3R | 37.5 N / 0.52 Nm | 6 | [68] |
| Phantom Premium 3.0 (3-DOF) | Serial | Trans. $838 \times 584 \times 406$<br>Rot. $335, 297, 260$ | 3P + 3R | 22 N | 3 | [68] |
| Phantom Premium 3.0 (6-DOF) | Serial | Trans. $838 \times 584 \times 406$<br>Rot. $335, 297, 260$ | 3P + 3R | 22 N / 0.52 Nm | 6 | [68] |
| Virtuose 3D Desktop | Serial | Trans. $520 \times 400 \times 220$<br>Rot. $360, 225, 130$ | 3P + 3R | 10 N | 3 | [69] |
| Virtuose 3D | Serial | Trans. $1330 \times 1020 \times 575$<br>Rot. $330, 270, 130$ | 3P + 3R | 34 N | 3 | [70] |
| Virtuose 6D Desktop | Serial | Trans. $520 \times 400 \times 220$<br>Rot. $270, 250, 120$ | 3P + 3R | 10 N / 0.8 Nm | 6 | [71] |
| Virtuose 6D | Serial | Trans. $1330 \times 1020 \times 575$<br>Rot. $330, 270, 130$ | 3P + 3R | 34 N / 3.1 Nm | 6 | [72] |
| Virtuose 6D TAO | Serial | Trans. $1070 \times 820 \times 458$<br>Rot. $330, 270, 130$ | 3P + 3R + 1G | 42 N / 5 Nm | 6 | [73] |
| Freedom-7 | Serial | Trans. $130 \times 160 \times 180$<br>Rot. $120, 90, 100$ | 3P + 3R + 1G | 5 N / 0.6 Nm | 6 + 1 | [74] |
| VISHARD6 | Serial | Trans. $880 \times 400 \times 310$<br>Rot. $360, 90, 90$ | 3P + 3R | 178 N / 54 Nm | 6 | [75] |
| HapticMaster | Serial | Trans. $460 \times 400 \times 360$ | 3P | 250 N | 3 | [76] |
| Omega.3 | Parallel | Trans. $160 \times 160 \times 110$ | 3P | 12 N | 3 | [77] |
| Omega.6 | Parallel | Trans. $160 \times 160 \times 110$<br>Rot. $320, 240, 140$ | 3P + 3R | 12 N | 3 | [77] |
| Omega.7 | Parallel | Trans. $160 \times 160 \times 110$<br>Rot. $240, 180, 140$ | 3P + 3R + 1G | 12 N | 3 + 1 | [77] |
| Delta.3 | Parallel | Trans. $400 \times 400 \times 260$ | 3P | 20 N | 3 | [78] |
| Sigma.7 | Parallel | Trans. $190 \times 290 \times 130$<br>Rot. $235, 200, 140$ | 3P + 3R + 1G | 20 N / 0.4 Nm | 6 + 1 | [79] |
| Falcon | Parallel | Trans. $100 \times 100 \times 100$ | 3P | 9 N | 3 | [2] |
| $HD^2$ | Parallel | Trans. $800 \times 250 \times 350$<br>Rot. $180, 180, 360$ | 3P + 3R | 19.7 N / 1.72 Nm | 6 | [80] |
| Delta.6 | Hybrid | Trans. $400 \times 400 \times 260$<br>Rot. $44, 44, 44$ | 3P + 3R | 20 N / 0.15 Nm | 6 | [78] |
| MEPaM | Hybrid | Trans. $142.5 \times 171 \times 187$<br>Rot. $180, 160, 180$ | 3P + 3R | 10.1 N / 0.56 Nm | 6 | [81] |
| VISHARD10 | Serial | Trans. $1700 \times 1700 \times 600$<br>Rot. $360, 360, 360$ | 3P + 3R | 170 N / 13 Nm | 6 | [82] |
| Compact 6-DOF Haptic Interface | Hybrid | Trans. $75 \times 75 \times 75$<br>Rot. $140, 140, 140$ | 3P + 3R | 10 N | 3 | [83] |
| Freedom 6S[b] | Hybrid | Trans. $240 \times 220 \times 220$<br>Rot. $320, 100, 100$ | 3P + 3R | 2.5 N / 0.13 Nm | 6 | [84] |
| CyberGrasp[b] | Hybrid | 1000 mm spherical radius | 5G | 12 N | 5 | [85] |
| CyberForce[b] | Serial | Trans. $304 \times 304 \times 495$<br>Rot. 133 | 3P + 3R | 8.8 N | 3 | [86] |
| SHaDe[b] | Parallel | Trans. $350 \times 350 \times 290$ | 3R | 60 N / 1 Nm | 6 | [87] |
| Mantis Desktop[b] | Hybrid | Trans. $400 \times 290 \times 200$ | 3P | 14.5 N | 3 | [88] |
| Mantis Large[b] | Hybrid | Trans. $1450 \times 1200 \times 600$ | 3P | 26 N | 3 | [88] |

[a] P, R, and G respectively stand for positional, rotational, and grasping DOFs.
[b] These devices are not investigated in the paper because they are less popular but included in this table to be inclusive.

are critical to an interface's performance [28].

### *5.1. Design Requirements*

Haptic interfaces are designed based on where and how they will be used and the requirements thereof. As explained in the following, the application of the interface should be analyzed in detail to determine what specific requirements are needed.

- Number of DOFs of the end-effector: The end-effector of each haptic interface needs a minimum number of DOFs to be able to perform a task successfully in the intended Cartesian space. Although some applications require lower DOFs in the end-effector, 7-DOF end-effectors that possess three translational and three orientational DOFs plus one more DOF for grasping motion are very common ones in the haptic interfaces.
- Size of workspace: Since the size of the workspace significantly affects the functionality of the haptic interface, the designer is expected to take a large enough singularity-free workspace into account to carefully make sure that the given task is executable effectively. Considering the working environment and the requirements of the task, the motion of the operator can be scaled up or down from the haptic device to the virtual environment. For example, working in a microscopic environment entails scaling down in most cases. Although haptic devices are not always required to imitate real-world movements, the size of the workspace highly matters when the haptic interface is meant to be used for training. Also, the designer should consider the range of motion of the joints when making a decision about the number of DOFs and the required workspace. Further, a small ratio of interface footprint to the workspace is required in order for the haptic device to be easily movable and integrable into the operation theatre.
- Number of DOFs of the haptic feedback: Theoretically, the number of DOFs of the end-effector obliges the designer to consider the same number of DOFs of the force and torque feedback. Practically, the designer determines the number of DOFs of the haptic feedback by compromising between how complex the interface can be, how much cost-effective the interface should be, and how much beneficial the feedback is to the system. The haptic feedback DOFs are not only imposed by the application requirements but also by the existing force and torque measured at the end-effector of the follower side. Furthermore, graphical cues can shoulder the role of some of the haptic feedback DOFs. In this regard, some researchers believe in the advantages of haptic feedback [89] whereas some others have shown that graphical cues enable the operators to perform the task as accurate and high-performance as the haptic feedback [44]. This means that the user can employ graphical cues sufficiently and profitably when they have no access to the haptic feedback. The haptic device displays a range of force that can be affected by the size of the workspace as well as the size and cost of different haptic interface platform. The factors contributing to the decision making of the designer also include the usual range of interaction forces demanded to perform the given task in the intended environment, the maximum force that humans can output while

maximizing the safety and minimizing the fatigue, and the minimum force that humans can sense. The designer should carefully ensure that the given task will be performed successfully and efficiently by employing the haptic device.

- Resolution of position and orientation sensing: The haptic device should sense the operator's command with a sufficient position and orientation resolution that is in turn application-dependent. For example, the surgeon's hand may move or orient with sub-millimeter or sub-radian precision in brain tumor surgery. Therefore, the haptic device must sense the command of the master side precisely and transfer it to the follower side.
- Force and torque feedback capability and resolution: The requirements of the intended task determine the required capability, range, and resolution of the force and torque feedback. To exemplify, an MIS commonly requires a range of force of $10\,N$ with a resolution of 0 to $2\,N$ [90]. Also, when rendering a solid object such as a bone in a medical intervention is needed, the force feedback of the haptic interface must enable the user to distinguish an object that is fixed in place. A difference of 5 to 15 percent of the reference force is distinguishable by the human's hand, according to the experts [91]. Any small change of the force and torque in the environment that should be distinguished by the user necessitates the high force and torque output resolution.

### *5.2. Haptic Interfaces with Serial Mechanism*

Serial mechanisms are commonly employed in a broad spectrum of robotic applications. In a solely serial mechanism, no passive joints are employed as the actuators are arranged in serial from the first to the last link of the kinematic chain. These mechanisms have several well-known advantages. For example, they are simple-to-design and fairly large-workspace mechanisms. Since the links and joints of these mechanisms are in a serial sequence, a step-by-step mathematical tool, such as the Denavit-Hartenberg algorithm, can be used to easily model and control the mechanism, particularly in positioning tasks. The main limitation of these mechanisms is their restricted dynamic behavior rooted in their fairly high mass. The high mass of the links is the consequence of the desire to have high structural stiffness. Moreover, the weight of the actuators that are expected to accelerate the following actuators of the chain adds to the mass of the mechanism. The structural stiffness with respect to the weight of serial mechanisms is also usually low because a single kinematic chain is expected to carry a load.

Given any limit in the accuracy of the joints of a serial mechanism imposed by cost or unavailability of component, the distal joints should sense the angular position more accurately than the proximal joints; similar to the distal joints of humans that have better joint angle resolution than the proximal joints [92]. However, Considering the general design criteria, the requirement of actuating remote joints in a haptic device that reflects force makes a serial mechanism less desired. In this case, most of the volume and mass of the joints come from the motors and gear reducers. Employing a cabled transmission to place actuators at the base of the mechanism is a solution, but the cable routing becomes more complex with each DOF.

PHANToM (3D Systems Inc., USA) is one of the haptic devices widely used all over the world [57, 93], which has been designed in different versions based on the application (see Figure 3). 3D Systems Touch is a fairly low-price and highly popular one that possesses six-DOF position and orientation sensing as well as a workspace of $160 \times 120 \times 70\,mm$. The maximum force feedback of the device in its three translational DOFs can reach 3.3 N. In the enhanced version of the device, called 3D Systems Touch X, the user has been provided with a larger workspace, higher resolution of positioning, and higher maximum force feedback ($7.9\,N$). PHANToM Premium is also a haptic device family produced by 3D Systems Inc. in different models to meet the expectations of the users by a much larger workspace and higher resolution of positioning. These models can also render the force feedback in a better range compared to the previous versions. PHANToM Premium 1.0, 1.5, and 3.0 are the three main devices in the family. In addition, a 6-DOF version of the PHANToM Premium 1.5 and 3.0 (three force and three torque feedback) have been presented to the market by the producer. The workspace of the 6-DOF PHANToM Premium 3.0 is $838 \times 584 \times 406\,mm$, and it can reach a maximum force and torque feedback of $22\,N$ and $0.52\,Nm$, respectively. Due to utilizing serial kinematic chains in the design, 3D Systems Inc. has succeeded in producing large-workspace haptic devices, but the force and torque feedback of these devices is inferior to that of haptic devices designed with parallel kinematic chains. Forsslund *et al* [94] designed an open-hardware *Do it yourself* (DIY) kit for novices to produce a spatial haptic interface equal to a PHANToM Desktop with some guidance and without specialized knowledge or tools, meant to be alterable by designers without the need for electromechanical expertise.

Virtuose (Haption, Soulgé-sur-Ouette, France) is also a haptic device family with a serially-chained kinematic design that can sense the position with 6 DOFs [69–73] (see Figure 4). There are two classes of 3D and 6D models in this family. The force feedback provided by the former class is 3-DOF active translational, whereas 3-DOF force and 3-DOF torque feedback are provided by the latter class. This family of haptic interfaces has a wide range of workspace size and force feedback capability. For instance, the workspace size and the maximum force of Virtuose 6D are $1330 \times 1020 \times 575\,mm$ and $34\,N$, respectively. Freedom-7 (produced by MPB Technologies Inc., Canada) is another serially-chained haptic device tailored for medical simulations [95] whose workspace is sized and is capable of providing high position resolution. This haptic device possesses a high resolution of positioning, low friction in the joints, and low apparent inertia. However, its small force feedback of up to $0.6\,N$ compared to that of other haptic interfaces is notable.

MAHI arm exoskeleton (developed at Rice University, USA) is a 5-DOF grounded exoskeleton-type haptic interface whose design objective was principally rehabilitation tasks and virtual environments-aided training [64, 96]. The majority of the workspace of the human arm can be covered by this device. Also, elbow, forearm, and wrist joints

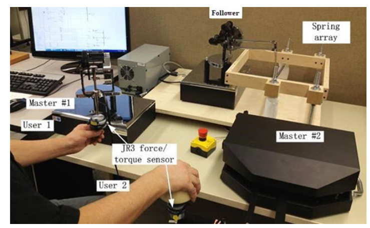
(a) Touch

(b) Touch X

(c) Touch 250 W

(d) PHANToM Premium 1.0

(e) PHANToM Premium 3.0



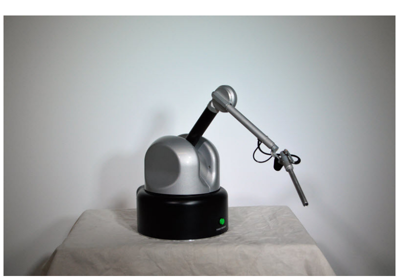

(f) PHANToM Premium 1.5

**Figure 3.** Samples of haptic interfaces with serial mechanisms [photos (a)-(e) by courtesy of 3D Systems and Canadian Additive Manufacturing].

(a) Virtuose 3D

(b) Virtuose 6D

(c) Virtuose 6D TAO



(d) Virtuose 3D Desktop

(e) Virtuose 6D Desktop

(f) Freedom 6S

**Figure 4.** Samples of haptic interfaces with serial mechanisms [photos (a)-(e) by courtesy of Haption GmbH].

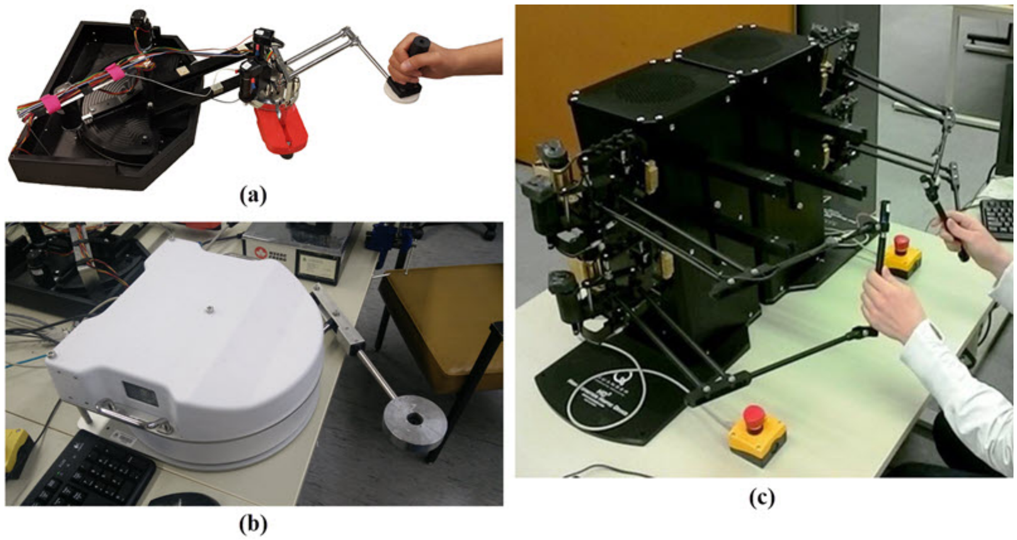



**Figure 5.** Haptic interfaces developed by Quanser Inc. (a) and (b) A serially-chained haptic device tailored for rehabilitation therapy; Autonomous Upper-Limb Stroke Rehabilitation Device or rehab robot. (c) A haptic interface called HD$^2$ High-Definition Haptic Device containing parallel mechanisms.

can be involved in the intended task by applying independent forces thereto. This interface is not working based on point contact, and various joints of the human can be provided with feedback that is controlled independently. Thanks to this independence, a therapist can effectively employ the exoskeleton for rehabilitation and focus the therapy on individual joints. In the same area of application, Quanser Inc. in partnership with the University of Toronto and Toronto Rehabilitation Institute (Toronto Rehab) has developed a haptic device called Autonomous Upper-Limb Stroke Rehabilitation Device for limb rehabilitation in stroke victims [97] (see Figure 5).

Ueberle *et al* [75] designed VISHARD6, a 6-DOF haptic interface with a workspace size of $880 \times 400 \times 310\,mm$. VISHARD6 has a relatively large workspace. However, an area in the center of the workspace is not available for haptic interaction due to interior singularities. Van der Linde *et al* [98, 99] also described the design and control of an admittance-controlled manipulator called HapticMaster (commercialized by FCS Control Systems, Netherlands). This large-workspace ($460 \times 400 \times 360\,mm$) and non-backdrivable interface is capable of providing large force and torque feedback [99]. It can reach maximum force feedback of $250\,N$ with three DOFs.

Impedance-controlled and admittance-controlled devices are dual in both cause-and-effect and performance. The impedance-controlled devices usually have low weight, zero backlashes, and no stick slip while renders low mass [100]. As a result, they have poor performance around higher forces and also high stiffness and mass. Due to the weight limits of the mechanism, employing complex end-effectors is also debatable. Admittance-controlled devices, on the other hand, are able to render a high stiffness. They are decent devices for large workspaces, master-follower tasks, and carrying end-effectors that are complex and high-DOF. Given a contact, the admittance-controlled devices intrinsically record the contact forces that encounter. The limitation of these devices is often the inability to render very low mass and friction, which means that the user will always feel the inertia and friction. These haptic interfaces suffer from the small force feedback over which mechanical properties (such as apparent inertia) and the friction of the joints of the interface can cast a shadow [24]. This drawback deteriorates the resolution and sensitivity of haptic feedback for the user. Rehabilitation applications typically demand a haptic interface capable of providing high force feedback, while the resolution of the force feedback is not important as much. Therefore, the admittance-controlled haptic interfaces are mainly designed for such purposes and optimized for human interaction and most useful in cases such as virtual assembly, haptics, and robotic rehabilitation. The haptic resolution, force depth, and impedance ratio are provided as performance indicators. This device cannot render torques and need an additional 3-DOF end-effector to this end. Admittance control is also commonly used in industrial manipulators because of high forces and stiffness. Since haptic manipulators always get in touch with a human physically, safety measures such as magnetic lock, emergency stops, and the workspace should be considered seriously.

### *5.3. Haptic Interfaces with Parallel Mechanism*

A closed-loop linkage with at least two chains that has an end-effector and a fixed based form a parallel mechanism. The actuators are usually fixed to the base or allowed for slightly moving in the space. Several kinematic chains included in the parallel mechanism handle the load that is applied to the end-effector and distributed thereon. As a result, parallel mechanisms are typically lightweight and structurally stiff. Also, the cut-off frequency of the dynamic transmission behavior and subsequently the transmission transparency of the haptic device are high. These properties significantly attract the attention of the researchers, but some drawbacks of parallel mechanisms should be noted in the meantime. For example, the small workspace of parallel mechanisms compared to the serial counterparts is thought of as a major drawback. Due to having several kinematic chains from the base to the end-effector, the kinematics and dynamics models of parallel mechanisms are more complex and nonlinear. The closed-form solution for the forward kinematics is not available for all configurations of a parallel mechanism [43]. Further, the position of the mechanism affects the transmission behavior, resulting in a parallel mechanism being considered directional and anisotropic within its workspace. Also, designing a high-DOF parallel mechanism is complicated because it requires several universal and spherical joints, which add to the friction and backlash of the mechanism.

A haptic interface designer should carefully consider singular positions of a parallel mechanism when planning for a closed-chain haptic device. In singular positions, at least two links of the mechanism become aligned. Singularity can occur in two situations. In the first case, which typically happens at the borders of the workspace of the mechanism, the transmission of the actuator's motion to the end-effector fails. In the second case, the transmission of the actuator's force or torque to the end-effector fails. This case, which typically happens within the workspace of the mechanism, leads to the state that no load can be carried by the end-effector. Quickly changing the transmission or gear ratio happens in a mechanism close to the singular positions to the point that the mechanism becomes locked at the singular position. In fact, the mechanism loses some DOFs in a singular configuration, putting the mechanism at risk or making its control impossible. Therefore, a designer is expected to analyze the singularities of the intended parallel mechanism to certainly avoid them during operation.

HD$^2$ High-Definition Haptic Device (produced by Quanser Inc., Canada) is a haptic interface from the family of interfaces designed based on pantograph kinematics, which possesses 6-DOF position sensing and provides 6-DOF feedback [101]. Thanks to the dual-pantograph kinematics of the mechanism, the workspace is as large as $800 \times 250 \times 350\, mm$ and the force and torque feedback can reach a maximum of $19.7\, N$ and $1.72\, Nm$, respectively (see Figure 5).

Omega, Delta, Sigma, and Lambda are categories of haptic interfaces in a family of parallel haptic interfaces commercialized by Force Dimension (Nyon, Switzerland) [102,103] (see Figure 6). Although these interfaces possess a smaller workspace compared to the serially-chained haptic interfaces, they provide relatively higher force feedback. Within the family, Sigma.7 with the largest workspace size of $190 \times 290 \times 130\, mm$ provides the highest level of force and torque feedback, which are $20\, N$ and $0.4\, Nm$, respectively, with a superior resolution of position in all six DOFs. Lambda.7 is the most recent haptic interface developed by Force Dimension possessing a larger base compared to sigma.7 and seven active DOFs in translation, rotation, and grasping. Falcon (produced by Novint Technologies, USA) is the economically-designed version of Omega.6 with a lower force feedback capability ($9\, N$), resolution of position, and the workspace size of $100 \times 100 \times 100\, mm$.

Asada *et al* [104] introduced the planar five-bar mechanism whose advantages are simple dynamics and low inertia. The Delta mechanism proposed by Clavel [105,106] is another 3-DOF parallel robot whose actuators are grounded. Three skewing parallelograms connect the base to the end-effector of the robot. Having an end-effector consistently parallel to the base is the main advantage of the Delta robot, which makes it a candid positioning mechanism for manufacturing applications. However, solving the forward kinematics of the Delta robot in closed-form is difficult. Hayward [107] also took the advantages of parallel mechanisms to propose a 4-DOF wrist structure in which three rotations, as well as a translation along the axis of roll rotation can be controlled.

It is worth clarifying that there might be other perspectives than ours when researchers analyze the kinematic chains of haptic interfaces that have been addressed here. As seen in some mechanisms in Figures 3 and 4, a parallelogram is used in the linkage design. That parallelogram is added to transfer the torque of the actuator located on the second joint to the third link to keep all actuators close to the base link and not in serial joints. However, by parallel kinematic design in this paper, we mean mechanisms that use the torque of the actuators in parallel to have almost the

(a) Omega 3 (b) Omega 6 (c) Omega 7

(d) Delta 3 (e) Sigma 7 (f) Lambda 7

**Figure 6.** Samples of haptic interfaces with parallel mechanisms [photos by courtesy of Force Dimension, Switzerland].

same contributions on the end-effector force/torque, which is the combination of all forces/torques and will result in a higher force on the end-effector. In serial designs, the actuator of the first and second joints are located far away from the end-effector and have less effect or contribution on the end-effector force than the third joint actuator. It means, if one uses the same actuators with the same torque capacities in serial and parallel designs, the parallel one (as defined in this paper) will result in more force on the end-effector. This note is also backed by Figure 2.

### *5.4. Haptic Interfaces with Hybrid Mechanism*

Combining serial and parallel mechanisms generates a hybrid kinematic device [108–110]. From the fixed base to the end-effector of a hybrid device, the parallel mechanism is connected to the base while the serial mechanism links the parallel mechanism to the end-effector of the device. This arrangement adds to the DOF of the end-effector. Tsumaki *et al* [83] designed a 6-DOF hybrid mechanism comprised of a 3-DOF parallel Delta robot [106] and a 2-DOF agile eye (a five-bar spatial mechanism) [111] serially mounted with a revolute joint. The advantage of the hybrid mechanism is providing decoupled translational and rotational motions while being easy to analyze and model kinematically. The drawbacks, on the other hand, are the inertia in motion and the volume of the robot rooted in the actuated joints of the wrist.

Delta.6 is a 6-DOF hybrid robot in which the combination of a 3-DOF wrist

(a) (b)

**Figure 7.** Samples of haptic interfaces with hybrid mechanisms. (a) Delta 6 [photo by courtesy of Force Dimension], (b) MEPaM [photo by courtesy of developer].

mounted on the end-effector of a 3-DOF parallel Delta robot [106] enables the mechanism to translate and rotate (see Figure 7). Abeywardena and Chen [81] proposed the Monash Epicyclic Parallel Manipulator (MEPaM) in which a cable-pully system is used to mount all actuators to a 3-leg 6-DOF parallel robot. Possessing back-drivability and also low mass and inertia of the legs qualifies the mechanism to be used as an impedance-controlled haptic device. Taking the motion of the mechanism into account, the MEPaM suits virtual environments as a haptic device. The workspace size of the MEPam is $142.5 \times 171 \times 187\,mm$. Dede *et al* [112] proposed a hybrid haptic device comprised of Hybrid-Spherical and R-Cube mechanisms. The kinematics of the device is easily analyzed thanks to the decoupled motions of the stated mechanisms.

### *5.5. Strengths and Weaknesses of the Reviewed Haptic Interfaces*

There are some pros and cons associated with each of the haptic devices reported in Table 2. The Touch haptic device [66] (formerly Phantom Omni) is one of the most commonly used haptic devices in the world. It can be considered as a device for beginners in this field. The main advantage of this device is the low cost while providing a basic and acceptable level of haptic feedback. The main drawbacks of this device include a very low level of the maximum force that it can generate ($3.3\,N$), and high friction in joints which causes undesirable resistance in free-motion. These two drawbacks have been addressed in Touch X haptic device [67] (formerly Phantom Desktop) by the manufacturer at the cost of a higher price. The kinematic design of Touch X is the same as the Touch; however, by including higher quality components such as electric motors and better manufacturing in terms of ball bearings and links, this device can provide a higher force at the end-effector ($7.9\,N$) with minimal resistance in free-motion as it has very low friction in joints and minimal apparent inertia due to low-weight components. The Phantom Premium haptic device is considered a high-end and high-quality haptic device [68]. There are multiple versions of this haptic device commercially available. Beside the Phantom Premium 1.0, which was the first version of this series and is obsolete now, the Phantom Premium 1.5 and 3.0 are offered in 3-DOF and 6-DOF versions. In the 6-DOF version, it can generate torques in three Cartesian axes in addition to the 3-DOF force generating capability. The Phantom Premium 1.5 comes in high-force or regular versions. All versions of the Phantom Premium 1.5 have the same kinematic and linkage design. The only difference in the high-force version is the actuators equipped with gearboxes to increase the torque on the motor shaft. This can be considered as a drawback of these devices as the user can feel the resistance of these gearboxes in free motion. The gimbal design (rotational DOFs) is the same in all these haptic devices. The Phantom Premium 3.0 has longer links and thus provides a much larger workspace than the 1.5 version. In all versions of this series, the torques at the end-effector are provided by tiny electric motors with gearboxes. This can be considered as a drawback of these devices as the quality of the provided torque is low, the user can feel the resistance of gearboxes, and because of the weight of these motors (although very tiny), the apparent inertia at the end-effector is high.

The Virtuose series haptic devices can provide a good level of force feedback in 3-DOF versions [69, 70] and a combination of high-force and high-torque feedback in 6-DOF versions [71–73]. The components of the device at the base are well-isolated in an enclosure. The footprint of the device is very small, making it a good choice for desktop applications. The handle of these devices is replaceable, which provides a huge advantage compared to many other devices. This advantage makes the device attractive for many applications as the hand-piece can be custom-designed to match the application. The weight balancing is provided by some springs compared to many other devices such as Phantom Premium, in which counterbalance weights are used. The counterbalance weight adds to the whole inertia of the device compared to springs; however, springs also create some resistance in free motion. This can be considered an advantage in some applications and a disadvantage in some others. The Virtuose haptic devices are good choices for industrial applications. The Freedom haptic device was designed for applications in which the resolution of the force feedback is of utmost importance (the lowest amount of controllable force generated by the haptic device) [74, 84]. This can be considered a huge advantage in applications such as brain surgery as the magnitude of forces is very low. This haptic device has very minimal apparent inertia at the end-effector, it moves very smoothly, and it can provide high-quality force feedback in comparison to other devices. However, it was not adopted well by the industry and is now obsolete. One of the main possible reasons in this regard can be the mechanism design of the haptic device. It uses a cable-driven design to transfer forces and torques to the end-effector. This design keeps the actuators (e.g., electric motors) at the base of the device and decreases the inertia; however, it makes the kinematic design very complicated, fragile, and prone to possible failure.

The HapticMaster haptic device was designed to provide ultrahigh force feedback to users (up to 250 $N$) [76]. It is an admittance (force-controlled) haptic device and thus can provide a very high stiffness. The magnitude of the force and the stiffness of this haptic device are of its attractive characteristics.

Another series of haptic devices are provided by Force Dimension [77–79]. These haptic devices take advantage of high-quality manufacturing in Switzerland. Most of these devices, such as Omega 3, Omega 6, Omega 7, and Sigma 7, use a parallel kinematic design. This kinematic design provides very high force feedback to the user, as the torque of all actuators are combined at the end-effector; however, it limits the workspace of the device. Some of these devices, such as Sigma 7 and Omega 7, provide a high grasping force for the user that can be an advantage in applications in which the grasping force plays an important role in the task quality. Another advantage of these devices is their small footprint. These devices provide a wide range of force generating capabilities and have been used in many applications such as robotic surgery (e.g., in the workstation of the second generation of neuroArm [113]). They can be recalibrated automatically once docked on the base and provide dynamic balancing for weight. The main disadvantage of these devices is the high manufacturing price, which makes them not attractive for many applications.

The Mantis haptic devices were designed and developed to provide light, affordable, and accessible haptic force feedback for many applications [88,88]. Usually, these haptic devices are used in multiple modules to provide multi-DOF force feedback to the user's hands. The light weight and ease of setup make these devices very attractive to many users as they can incorporate multiple devices in their workstation designs for a broad range of applications. They can also be used as light-weight robotic arms for, for instance, mobile robotics and telerobotic applications. They provide a good range of force feedback (up to 26 $N$) with a simple yet effective kinematic design. The Mantis Large provides a huge workspace for applications requiring such. The small footprint and configurator software design are other advantages of these devices.

## 6. Evaluation Methods for Linkage-Based Haptic Interfaces

The development and implementation of evaluation methods to experimentally measure the performance of haptic interfaces has been a matter of debate since the 80s when force-reflecting hand controllers (the former name of haptic interfaces) found a place in teleoperation. In order to know the requirements of a device, the physical performance of the device should be evaluated. The performance can be evaluated by employing the measures and characteristics of robotic platforms. A haptic interface is primarily expected to command the follower side or virtual environment based on the orders of the operator and also obtain applicable sensory information, particularly forces, from the remote side and reflect it back to the master side. Operator-interface interaction must be basically free from any kind of interference rooted in the kinematics and dynamics of the device. According to Jex [114], the performance of a haptic device is approved given passing four tests. The interface passes the first test given simulating a piece of light balsa wood with small inertia and almost zero friction. Simulating a sudden hard stop is the second expectation from the device in the evaluation tests. The third test focuses on the ability of the device to simulate the Coulomb friction, meaning that the device should go to the zero-velocity state if the operator stops holding the handle. Lastly, the simulation of mechanical detents without lag and with a sudden transition in the fourth test is expected from a haptic device.

A number of other researchers also investigated the evaluation methods for haptic devices. For instance, McAffee and Fiorini [115] recognized the principal characteristics that affect the performance of the hand controllers and then compared the performance of the existing devices quantitatively. The technology of robotic actuators was comparatively analyzed by Hollerbach *et al* [116]. The performance measures of haptic interfaces were defined by Hayward and Astley [55] theoretically, while Morrel and Salisbury [117] worked on formalizing the performance measures for coupled micro-macro actuators. Furthermore, Ellis *et al* [56] demonstrated how to experimentally measure the performance of these devices.

The methodologies existing for the physical evaluation of haptic interfaces are categorized based on the properties of passive (unpowered), powered, and controlled robotic systems. The actuation-free investigation gives the space to characterize passive systems. While electronic and control elements play no role, the design of the mechanism and structure determines the properties of passive systems. The properties of powered systems, on the other hand, state how capable the actuation and sensing of the device are. This capability is identified by investigating the flow of input and output individually and separately without implementing any control algorithm. In the end, the performance of the whole controlled system is specified by forming a loop that includes the human, mechanical structure, actuation system, and sensors.

A haptic interface is basically expected to move similar to all robotic mechanisms. Kinematic analysis to find the pose and velocity of the mechanism, therefore, helps us to define how capable the mechanism is and where the boundaries of the motion are. The design of the robot, how to select the actuators, sensors, and the control method are all related to the kinematics of the interface, which includes both joint space and task space analyses. The Jacobian matrix $J$ relates the velocities and force/torque of the robot in the joint and task spaces as

$$\dot{X} = J(q)\,\dot{q} \tag{1a}$$

$$\tau = J^T(q)F \tag{1b}$$

where $\dot{X}$, $\dot{q}$, $\tau$, and $F$ are the vectors of end-effector velocity, joint rates, joint torques, end-effector force/torque, respectively. The Jacobian is a function of the pose of the mechanism and serves as the fundamental element of the kinematic analysis of the robot. A set of factors contribute to the kinematic performance analysis of a robot, including DOFs, singularities of the robot, kinematic isotropy, workspace, and the indices of manipulability and dexterity.

- Workspace: The shape and volume of the workspace are defined based on the configuration of the mechanism. The workspace is normally represented graphically in the form of a basic shape or an envelope. The reachable and dexterous workspaces can be attributed to a robot. The setpoints reachable by the end-effector form the reachable workspace, whereas the points reachable by the robot in any arbitrary orientation represent the dexterous workspace. Early methods used numerical and algebraic analyses to define these workspaces of a mechanism. For example, Kumar and Waldron [118], Yang and Lee [119], and Tsai and Soni [120] used numerical techniques for this purpose. Numerical methods are superior to algebraic ones because they easily include kinematic constraints. The limitation of these methods is that universal principles or insights of design are difficult to reach. Gupta and Roth [121] and Gupta [122] introduced an algebraic method of workspace characterization based on topological analyses. In this method, the concept, as well as the existence conditions of holes and voids of the workspace are first presented. They also analyzed what shape the dexterous and reachable workspaces may have. Further, Freudenstein and Primrose [123] and Lin and Freudenstein [124] studied the workspace analysis, precisely developed relationships between the kinematic parameters and workspaces, and optimized the workspace volume of a class of manipulators that have three joints. Then, Vijaykumar *et al* [125] analyzed workspace optimization in a more general way. They defined the performance of the manipulator in terms of the dexterous workspace and showed that the elbow manipulator is the optimal six-revolute (6R) mechanism if a set of constraints on the Denavit-Hartenberg parameters are satisfied.

- Dexterity: Moving and applying torques and forces in arbitrary directions indicates the dexterity of a manipulator. The dexterity can be measured based on several performance metrics. The term manipulability, introduced by Yoshikawa [59], is defined as

$$\mathcal{M} = \sqrt{\det(JJ^T)} \tag{2}$$

which quantitatively shows to what extent the manipulator can arbitrarily change the pose for a given posture without any difficulty. A measure of distortion ascribed to the Jacobian was proposed by Salisbury and Craig [126]. The largest singular value $\sigma_{max}$ of the Jacobian divided by the smallest singular value $\sigma_{min}$ defines the condition number, $\kappa$, of the Jacobian as

$$\kappa = \frac{\sigma_{max}}{\sigma_{min}}. \tag{3}$$

Near the singularities of a manipulator, the condition number advances toward infinity. Thus, using the reciprocal of the condition number, $1/\kappa$, which is limited to $[0, 1]$ is more convenient. The dependency of the condition number to the pose of the robot is a source of local information about the dexterity. Integrating the condition number over the entire workspace [127,128] introduces the global conditioning index (GCI) as

$$\eta = \frac{\int \frac{1}{\kappa} dW}{\int dW} \tag{4}$$

which is a more general metric compared to the condition number. The movement isotropy of the mechanism over the workspace is represented by the GCI. If the GCI approaches 1, the even feel becomes more through the workspace [129].

- Structural stiffness: High structural stiffness in a robot is an asset because the position of the end-effector is reliably calculated given stiff links and joints and also the structural response of the robot is better when loaded dynamically. In order to measure the structural stiffness of a haptic interface, which is usually performed at the endpoint, the joints should be locked. By putting a loading typically a dynamometer on the endpoint, a dial indicator placed at the same point measures the deflection of the system. Therefore the structural stiffness of the system can be calculated as applied force divided by the deflection of the system along the direction of the applied force.
- Apparent inertia: Asada [130] and Khatib [131] introduced the concept of generalized inertia ellipsoid (GIE) as the geometric shape formulated by

$$\Lambda = (JM^{-1}J^T)^{-1} \tag{5}$$

where $M$ stands for the matrix of inertia in the joint space. The formulation describes the dynamic capability of a robotic mechanism. Apparent inertia, in a haptic interaction, states how much inertia the operator feels while moving the end-effector.

- Force feedback capability: The manufacturer of a device is usually expected to provide the maximum capability of the device to produce output in static conditions. The maximum force that a haptic interface can produce is of the same nature. This metric is specified by either transient peak force or maximum continuous force. Heat dissipation limits the duration of the former force. Therefore, the latter force is a better metric to evaluate the performance of haptic devices. To this end, designers are willing to identify the maximum force that a haptic interface can apply to the operator's hand. The Jacobian matrix relates the motor torques, $\tau$, to the forces/torques applied to the endpoint of the robot, $F$, according to

$$F = (J^T)^{-1}\tau = J_F\tau. \tag{6}$$

Therefore, the bounds of the force given a unit torque vector ($\|\tau\| = 1$) are defined as [23]

$$\sigma_{min}(J_F) \leq \|F\| \leq \sigma_{max}(J_F). \tag{7}$$

- Sensitivity: In a haptic interface, (6) gives the motor torque required to generate a desired force at the end-effector. The encoders of the interface usually measure the current position relative to the position of the interface after restart (zero position). The home position is also where the arms and motors are at the right angles with respect to each other [132]. If any offset between the zero and home positions appears in the forward kinematics and the Jacobian matrix, the measurement of $q_i$

becomes erroneous, which in turn deviates the actual force reflected to the operator from the intended force. Suppose that all encoders of the interface have a small offset error, $\delta$, in their measurements as

$$\hat{q}_i = q_i + \delta \tag{8}$$

where $\hat{q}_i$ and $q_i$ are the measured and actual positions, respectively. Relying on (6), the torque of the motors relates to the intended and actual force feedback as

$$\hat{F} = J_F(\hat{q}_i)\tau \text{ and } F = J_F(q_i)\tau. \tag{9}$$

The normalized error of the force feedback is calculated as [23, 133]

$$\gamma = \frac{\left\| \hat{F} - F \right\|}{\|F\|}. \tag{10}$$

Considering the small offset error, a Taylor series expansion around $q_i$ gives $J_F(q_i + \delta) \approx J_F + \delta J^1(q_i)$ resulting in

$$\gamma = |\delta| \cdot \left\| J^1 \tau \right\| / \left\| J_F \tau \right\|. \tag{11}$$

Given $\|\tau\| = 1$, without loss of generality, a normalized force feedback error of $\gamma \leq \gamma_1$ requires the initial error, $\delta_0$, to satisfy $\delta_0 \leq \min \frac{\sigma_{max}(J_F)}{\sigma_{min}(J_F)}$. In addition, the normalized force feedback error in the case of initial angle offset of $\delta_0$ is limited at each point withing the workspace of the device according to $\gamma \leq |\delta_0| \frac{\sigma_{max}(J_F)}{\sigma_{min}(J_F)}$.

## 7. Redundant Linkage-Based Haptic Interfaces: Future Directions of Haptic Interfaces for Medical Applications

Kinematically redundant haptic interfaces are possible solutions to deal with the design trade-offs stated in the previous sections. The number of DOFs in such manipulators is higher than what is needed to perform a task successfully. In a haptic interface possessing joint space redundancy, inner joint motion, which is also called self-motion, is feasible. It means that one can move joints while the pose of the end-effector remains unchanged. An interface can be expected to fulfill primary and secondary tasks at the same time [134]. Position, force, or impedance control of the manipulator in the task space are the examples of primary tasks while the robot is expected to avoid singular points in the workspace, reach a higher manipulability, or maximize the force feedback as the secondary objectives. This redundancy is present in the human arms and fingers as well [135]. As reported by Schaal and Schweighofer [136], complex dexterous tasks given to human users are performed by utilizing kinematic redundancies in the arm accompanied by a compliant control in the task space. Nisky *et al* [137] also studied the performance of experienced surgeons and reported that arm redundancy is employed by skilled surgeons more than the novice counterparts to stabilize hand movements.

Redundant manipulators have been widely used in industrial sectors [138]. Ficuciello *et al* [139] reported the benefits of the self-motion in the control of physical human-robot interactions because it improves interaction performance as a secondary objective. Despite having desirable features, the design and control of redundant haptic interfaces (RHIs) have not captured the attention of the community at a high level. The community has been majorly focused on the application of redundant robotic arms in object manipulation tasks or physical human-robot interactions in industrial domains. A range of reasons may be counted for the few studies conducted on the RHIs design. Compared to a non-redundant haptic interface (NRHI), a higher number of joints, links, and actuators add to the design complexity and cost as well as the required computational power of an RHI. The higher computational power is the consequence of the demand for a complex algorithm to control the extra DOFs. The mechanical design of industrial robots is mainly focused on enabling the robot end-effector to move quickly or carry large payloads. The design of a haptic interface, on the other hand, should satisfy these two opposing requirements while possessing back-drivability and also low apparent inertia and friction. That is why the design of haptic interfaces is more constrained, and their design and control are more challenging.

To the best of our knowledge, the only commercially available haptic interface is the user interface of the da Vinci Surgical System (Intuitive Surgical Inc.), but no design-related information is available for proprietary reasons. The user interface of the da Vinci Surgical System is described in [140]; however, there is no quantitative information made available. The redundant user interface of the system has an extra DOF that is meant to allow the handle of any tool attached to a follower device to move in space in ways similar to the motions that a surgeon might use with their tools in a non-robotic surgery. A processor shoulders the responsibility of actively driving the extra DOF of the device to keep the device far from the singularities [140]. In the da Vinci master interfaces, it is debatable whether these qualify as haptic interfaces. Although the redundant linkages of the master hand controllers are actuated, the actuation does not correspond to the sensed properties of the follower manipulators. However, they are included in this paper as they have the potential to provide haptic feedback to the user and thus can be considered as haptic interfaces. Further, as far as we know, the only paper on the design of a redundant haptic interface is [82]. VISHARD10 has a relatively large workspace of cylinder $1700 \times 1700 \times 600\,mm$ with the maximum force feedback of $170\,N$. In comparison to the data available in Table 2, VISHARD10 has both a larger workspace and a larger force feedback capability.

As the RHIs are still in their infancy, there are not much data available for quantitative comparison of redundant and non-redundant haptic interfaces. Regardless, the RHIs have intrinsic advantages over NRHIs in terms of better kinematic and dynamic characteristics, for example, increased manipulability (one result of which is reduced friction) and reduced apparent impedance [24]. The intrinsic advantages of RHIs over NRHIs in terms of meeting the criteria in Section 4 has been investigated in [24]. These advantages depend on the kinematics and dynamics of RHIs, not on any algorithm or computer-based control. Manipulability index, the size of the workspace, and the accuracy of force feedback, which are measures of the kinematic performance, in RHIs can reach a level higher than those of the original NRHIs by only adding to the

DOFs of the base. Additionally, the measures of the dynamic performance, which are apparent inertia and friction, in the RHIs are at a lower level compared to the NRHIs [24]. The closed-loop control of the RHIs at the joint level is benefited from the redundancy to satisfy secondary objectives. A null-space controller, in parallel to the main controller devised for primary objectives, attempts to achieve secondary objectives. By manipulating the extra DOFs of the interface properly, the RHI redundancy is able to decrease the reflected friction of the joints at the end-effector [141]. As a result, the haptic feedback resolution, also called sensitivity, will be increased for the user. A psychophysical experiment conducted in a simulated soft tissue palpation task validates how much the force perception of the user has been improved [24]. The effect of redundant and non-redundant user interfaces on the perception of the virtual stiffness is evaluated by conducting perceptual experiments. Experimental results reveal that the ability of the user to discriminate the stiffness of the tissue is enhanced by employing the redundancy in the haptic interface and mitigating the distortions rooted in the kinematic and dynamic properties of the interface.

Without adding to the length of the links of the RHI, Baser *et al* [142, 143] designed a 7-DOF RHI whose workspace was fairly larger than that of 6-DOF NRHIs. Adding one extra DOF to the base of haptic interfaces to in turn add to the size of the workspace was proposed by Barrow *et al* [144], Kim *et al* [145], and Gosselin *et al* [146], but the redundancy resolution was not debated in their report. The teleoperation of a redundant robotic manipulator was studied by Nath *et al* [147] by employing an RHI with the same number of DOFs.

Actuation redundancy, which is exclusively for parallel robots [148], is another debatable category of redundancy in the haptic interface design [149–152]. Compared to parallel robots, serial robots have a larger workspace and straightforward closed-form forward kinematics solutions. On the contrary, parallel robots can produce higher force feedback, and rendering an environment with high stiffness is possible by incorporating the actuation redundancy. However, the actuation redundancy enforces a limit such that the apparent inertia and reflected friction at the robot end-effector increases due to having actuators in place of passive joints. Further, the forward kinematics of parallel robots should be solved numerically, which is computationally inefficient.

The redundancy resolution problem in redundant robots deals with how to determine the motions of the joints in order to achieve sub-tasks in the joint space in parallel to the primary task in the Cartesian space [153]. This problem is solved for the standard redundant robots in a broad range of methods among which reduced gradient-based method [154], damped least-squares inverse Jacobian method [155], and the weighted inverse Jacobian method [156] that can be extended to the RHIs. The sub-tasks include but are not limited to avoiding joint limit [157], obstacle, and singularity [59, 158] as well as maximizing manipulability. Joint velocity, acceleration, or the torque of RHIs in the null space of the Jacobian matrix can be adjusted without affecting position, velocity, the force/torque of the end-effector, which in turn results in the self-motion [159]. Hence, as the second task in some applications, a suitable auxiliary function is designed to control the self-motion and a sub-task.

Torabi *et al* [141] developed a null space controller for the RHIs that uses a previously-introduced index of teleoperation manipulability in [25]. The controller matches the kinematics of the RHIs to that of the follower robot to reach a higher teleoperation performance. The controller also modulates the redundant DOFs of the interface to reshape the ellipsoid of manipulability toward that ellipsoid of the follower robot. This ellipsoid, in fact, shows the kinematics of the robot geometrically. The kinematics of the haptic interface and the follower robot is matched by reshaping the manipulability of the haptic interface. The redundancy of the RHI allows us to increase the manipulability of the RHI-follower system and transfer the dexterity of the follower robot to the user more intuitively. The performance of the suggested control method is experimentally validated, which demonstrates that the null space controller empowers the user to control the force or velocity of a surgical robot and keep the control effort needed to perform a teleoperated task at a minimum.

A contact-aware null-space controller for RHI is proposed in [160]. They first introduced a task-dependent null-space controller that controls the internal motion of the RHI decently to reach the desired performance. The desired performance is reaching a low level of back-drive friction given free-space motion and soft contact, or a high level of force feedback given stiff contact. By developing a transition method, they adapted the varying objectives of the null space controller according to the task. The discontinuities of the control signal are stopped using the transition method. To keep an eye on the distance of the joint torques from the saturation levels and inform the transition method, an actuator saturation observer is proposed. Caused by the proposed controller, the feelings of soft and hard contacts can be recreated with a fidelity that is higher than that of a conventional NRHI. The effectiveness of the controller is verified experimentally in three phases of soft contact, hard contact, and transition.

By leveraging the kinematic redundancy of the interface, Torabi *et al* [161] proposed an actuation saturation compensation method to enable an RHI to produce better force feedback. The method is focused on the null space of the Jacobian of the RHI, taking the extra torques of actuators, and distributing them among the available yet unsaturated actuators at the joints. The method equips the haptic interface designers with the ability to use smaller actuators with lower motor inertia and friction. These properties are beneficial since the interface should be essentially low apparent inertia and friction to be able to candidly recreate the feeling of free space motion. Thanks to the proposed method, the torque that is required to render a stiff environment can be distributed among small-capacity actuators optimally. The actuators are subject to saturation without the distribution. In addition to the force reflection and actuator saturation compensation that are respectively the primary and secondary objectives, the enhancement of the manipulability of the RHI toward the direction of the task is also proposed as the tertiary objective. The latest objective acts given the first and the second objectives are possible to succeed, and the interface still has redundancy available. A four-DOF planar haptic interface is used to experimentally verify that the control of the interface using the method is practical.

## 8. Non-Linkage-Based Haptic Interfaces

A variety of interesting and novel technologies have been developed in recent decades to actuate non-linkage-based haptic interfaces. These actuators can work based on vibration, acoustics, electrostatic friction, magnetic interaction, magneto-rheological fluids, soft materials, or shape memory alloys. Though these actuators are mostly not yet commercially available, their potential in developing portable haptic devices is very high. Although our review on the design of linkage-based haptic interfaces cannot thoroughly span the range of these interfaces, we see up-and-coming trends in the community toward the design of these haptic devices as well. These technologies are briefly introduced in this section as follows.

### *8.1. Vibration-Based Haptic Interfaces*

Vibration-based actuators produce feedback against the users' fingertips via the vibratory motion of a motor, creating a tactile experience for the user. One of the best-known technologies used in haptic interfaces and an excellent example of vibration-based actuators are piezoelectric actuators. The application of a voltage causes a piezoelectric crystal to deform, producing a force very useful for providing tactile feedback. These actuators cannot create displacements beyond a few microns, making them unsuitable for any sort of large force feedback. However, they can produce vibrations in the range of 1 kHz; enough to simulate a variety of tactile feedback textures [2, 162]. An example of a device with a vibrotactile component is the HapThimble [163], a device that encapsulates the tip of a user's finger with a cap that holds a motorized spring used to produce pseudoforce along with vibrotactile feedback. As with any actuation method focused on tactile feedback, it is likely that some other actuator(s) will be needed for force feedback in a surgical setting to assist with the guidance of a surgeon's hand's path, for instance.

### *8.2. Acoustics-Based Haptic Interfaces*

Acoustically actuated devices use ultrasound or other sound-producing actuators to produce tactile feedback in a similar way to the use of piezoelectric actuators, and share the same inability to produce force feedback but the same ability to produce refined tactile sensation due to their high frequencies. An example of a device with an acoustic actuation component is Grabity [164], a wearable device made to simulate grip opposition forces and weight of virtual objects. Here, in addition to a unidirectional brake used to create grip opposition feedback, two voice coil actuators create a force tangential to the motion of each finger pad, providing vibrotactile feedback. The tactile feedback here is provided as a secondary component to force feedback.

### *8.3. Electrostatic Friction-Based Haptic Interfaces*

Actuating haptic interfaces via electrostatic friction is another method among the existing approaches. Here, the surface of the user's finger is placed against a surface and becomes part of an electric field that causes attraction of the skin to the interface surface, increasing friction without the need for a mechanical component. An example of a device that takes advantage of this phenomena is FinGAR, or *Finger Glove for Augmented Reality* [165], a wearable haptic device in which electrical stimulation produces a sense of pressure and low-frequency vibration while mechanical stimulation is used to create high-frequency vibrations and skin deformation. Note that an electrostatic field may increase friction and give a feeling of adhesion between the user's finger and the device. However, some other sort of actuator is necessary to activate that frictional force to produce a varied rate of deformation. This electrostatic friction force could be a useful way for surgical devices to provide a sense of surface tension of tissues to be operated on, as one instance of its potential use in the medical field. Potentially, a similar device could produce an electrostatic force between a stylus used to simulate a scalpel or other medical implement and the position sensing mechanism to which it is attached.

### *8.4. Magnetic Interaction-Based Haptic Interfaces*

Some haptic devices use magnetic interaction, such as MagTics [166]; an interface made for use in smart watches and fitness trackers to produce more detailed tactile feedback than the standard vibration-based actuators used in most such devices. Here, a dense set of magnetically actuated bidirectional tactile pixels (taxels) are used to create sophisticated tactile feedback along the user's skin. This device demonstrates minimal power consumption with a great deal of flexibility and a thin form factor, but it might be inappropriate in those medical settings in which magnetic interference could be an issue.

### *8.5. Magneto-rheological Fluid-Based Haptic Interfaces*

Haptic interfaces could take advantage of the properties of certain magneto-rheological fluids (MRF), materials whose viscosity behavior shifts depending on an applied magnetic field. Others use electro-rheological fluids (ERF) instead, whose viscosity shifts due to an electrical field [167]. Yield stress generally causes this phenomenon. The field amplifies the phenomenon, and turning the field off can take it back to the original condition. With ERF, frequencies of near 1kHz can be developed being states, allowing for their use in a haptic device. Their main drawback is the high voltage needed for these devices (2-4 kV per mm gap between electrodes), which is thought of as a potential safety issue [168]. As well, the used fluid can lack homogeneity, leading to a reduced power conversion within the actuator over time. As for MRFs, these appear to be mainly used in laboratories due to the expense of the fluids and their heavy nature (as iron particles are involved) [169]. While there may be some uses for these interfaces in medical applications over time, safety and weight issues make them unlikely to be trendy choices overall [2].

### *8.6. Soft Material-Based Haptic Interfaces*

Soft flexure or compliant devices could be of greate interest for medical applications, such as with devices meant to assist with patient physical therapy, as they use soft materials that are therefore less likely to demonstrate safety issues. These would also be useful to simulate soft tissues virtually. An example of a soft flexure device is the Dielectric Elastomer Actuator-based tactile display [170], which uses smart elastomers to produce the sensation of soft surface touch. These elastomers are electroactive and produce a tunable force through an electrically deformable soft interface. Mountable on fingertips, these can be driven individually with an optical tracking system used for position determination.

### *8.7. Smart Material-Based Haptic Interfaces*

A related technology of potential use in haptic interfaces design is that of shape memory alloys (SMA), which return to their original shape when exposed to an appropriate temperature. Providing resistance during this transformation will cause an SMA to produce a force, which might be used to design a force feedback device [171]. These actuators can produce a great deal of work per unit volume, more than most actuators. However, they are dependent on temperature and require a long relaxation period, which might make them less functional in a haptic interface. A more promising similar technology is that of electroactive polymers, which change shape or size due to electrical stimulation. These are flexible, highly dynamic, light, resilient to damage, and efficient in terms of power, making them very useful in bionic robots [172] and microelectromechanical systems [173]. These technologies can therefore be used in microstructures of medical microdevices. However, the requirement of high voltages and possessing characteristics that are not fully understood make them not precisely the right polymers for the purpose. Also, they are challenging to manufacture and cannot be mass-produced [2].

### *8.8. fMRI-Based Haptic Interfaces*

In investigations into the neural mechanisms of the fingertips, functional magnetic resonance imaging (fMRI)-based devices were introduced, but their functionality was provided generally unpleasant experience. A Cable-driven fMRI-compatible haptic interface was therefore developed that consisted of a scanner bore, interface, and a shielded electromagnetic actuation system placed at the end of the scanner bed [174]. Low inertia, high stiffness cables were used to attach this actuation system to the interface for whole-brain non-invasive advanced brain research with increased temporal and spatial resolution. Another device called MOTORE system [175], which is light, portable, and user-friendly, has proven useful for rehabilitation due to its lack of calibration requirements. This device is an omnidirectional mobile cart with a handle for the user that relies on three omnidirectional wheels to produce force feedback. A gearbox can be added between the handle and the cart of the device for reducing the operational force in the case of rehabilitation. An altered version might be usable for some teleoperations as well.

### *8.9. Magnetic Levitation Haptic Interfaces*

In the 80s, Ralph Hollis proposed using Lorentz forces to levitate rigid bodies [176]. The idea was then implemented as a precision robot wrist called Magic Wrist [177–180] and a haptic interface [181, 182]. Later, the first relatively large workspace magnetic levitation haptic device was fabricated by Berkelman *et. al.* [183, 184] to be used for, for instance, psychologically investigating hard contacts, synthesizing and precepting textures, and analyzing deformable object perception. The performance, usability, and cost-effectiveness of the haptic interface were improved by Hollis *et. al.* in the following works. They developed a coarse-fine teleoperation system based on the magnetic levitation idea [185, 186]. It was finally commercialized by Butterfly Haptics (Pittsburgh, USA), called Maglev Haptics [187, 188]. The mechanical complexities of the Maglev Haptics (related to inertia, friction, and backlash, for example) have been eliminated for a magnetically-levitated lightweight moving part called *flotor*. The flotor is rigidly attached to the user's handle, floated in a strong magnetic field provided by permanent magnets of the motors' stators employed in the device. When the user moves the handle within its motion range, optical sensors track the flotor's pose. In a bidirectional communication between the user's application and the handle, the flotor's position is transferred to the application, while the forces and torques are sent to the handle. Maglev Haptics has a high resolution, high position and force bandwidth, and small workspace, which can be effectively covered by scaling and indexing methods.

### *8.10. Wearable Haptic Interfaces*

Wearable haptic devices are among the most common non-linkage-based haptic interfaces with different applications ranging from gaming and virtual/augmented reality to teleoperation and medical surgeries. These interfaces enable the users to feel touching of an object using cutaneous and tactile feedback [165, 189]. Wearable devices employ cutaneous feedback sent to the fingertips and hands in, for example, shape recognition and edge detection tasks. These lightweight interfaces are relatively expensive yet easy-to-design and fabricate. The hRing [190] is a haptic device consisting of two servo motors and a belt that is placed in contact with the user's proximal finger phalanx. It can be used in augmented/virtual reality, hand rehabilitation, and the virtual training of medical students and practitioners for surgical operations. LinkTouch [191] consists of a fingerpad, an inverted five-bar mechanism, and two motors. The rotation of the motors in the opposite direction generates pressure and then sends 2-DOF force feedback to the fingerpad. This interface can be employed for finger rehabilitation. HapThimble [163], MagTics [166], Grabity [164], and FinGAR [165], all introduced in the previous subsections, are also samples of wearable haptic interfaces. The number of wearable haptic devices is such high that dedicated review papers have been published in this regard in the last decade [192, 193].

For the sake of inclusion, more wearable haptic interfaces are presented at the end of this section within which the readers can find a range of devices for different applications; hBracelet for the distributed mechanotactile stimulation of the upper limb [194], HapWRAP as a soft growing wearable haptic device [195], HapPro for proprioceptive feedback [196], Wolverine [197] and DextrES [198] for grasping in virtual reality, ExoTen-Glove as a twisted string-actuated haptic glove [199], RML glove as an exoskeleton glove mechanism for medical training and rehabilitation [200], ForceHand as a pneumatic artificial muscle-actuated wearable glove [201], Tacsac with capacitive touch-sensing capability for tactile display [202], WeHAPTIC for accurate position tracking and interactive force control [203], KinoHaptics as an automated wearable haptic physio-therapeutic system for post-surgery rehabilitation and self-care [204], Mood glove for enhancing mood music in film entertainment [205], Rutgers Master II-ND glove for dexterous interactions with virtual environments [206], and PianoTouch for piano instruction and passive learning of piano skills [207].

## 9. Design Requirements for Haptic Devices in Medical Applications

There are unavoidable trade-offs involved in optimizing design specifications when conforming to a specific application. In teleoperated surgery, for instance, the maneuverability, sensory feedback, degrees of freedom and workspace of the haptic interface should, if possible, match the intuitive understanding of the surgeon as regards what would be their hand's in-person workspace to best emulate for them conventional surgery. Designing a new interface or selections from commercially available choices is, therefore, an application-driven process; a detailed analysis of the specific surgical application is required to determine the specifications of the interface [2]. The following general specifications concerning telesurgery have been determined by analyzing freehand surgery in a conventional environment.

- An interface's end-effector needs a minimum number of DOFs for the task it must be used to perform in Cartesian space. Most surgical applications require 7 DOFs; 3 for orientation, 3 for translation, and a final one for grasping motion. Some surgical applications, however, require lower DOFs for the end-effector. An example of this would be needle insertion, which is a 5-DOF action (3 DOFs for translation and 2 for orientation) [2].
- The interface's haptic feedback mechanism should ideally contain the same number of DOFs for force and torque feedback as the number of DOFs of the end-effector, but in actuality, this number is a trade-off between cost, interface complexity, and

the level of benefit involved in receiving the feedback. Additionally, the end-effector of the follower's existing force and torque measurements determine the maximum force and torque feedback DOFs for the haptic interface. As well, some haptic feedback DOFs can adequately and cost-effectively be replaced by graphical cues. While many studies show that haptic feedback is beneficial [89], some have found in at least some instances that task performance and accuracy can be comparable when relying instead on graphical cues [2, 44].

- For sensing position and orientation of the end-effector, the resolution needed must suit the surgical application. For example, ablation of a brain tumor necessitates sub-radian and sub-millimeter precision, a resolution that must be sensed by the interface and passed on correctly to the follower [2].
- The interface requires a workspace large enough to make certain that an action can be taken, along with one free of singularities. Therefore, motion scaling between the follower and the interface is quite important and requires close attention. As well, the footprint-to-workspace ratio of the interface needs to remain small enough for ease of integration and mobility within the operating theatre [2].

Those interfaces that satisfy more stringent requirements would provide better performance, but such devices are expensive, more complex than necessary, and computationally expensive for real-time control. A more cost-effective and straightforward method than designing a new interface to fabricate is using a commercially available interface purchased and modified as needed. This, however, means that not all the characteristics of the interface will be accomplished. Haptic interaction fidelity perhaps becomes limited due to the few minor alterations that might be made to commercially available interfaces. If an appropriate commercial device does not yet exist, in the instances of more sensitive uses such as telesurgery, it may be best to design a new device specific for the application rather than risking patient safety. However, some less risk-critical medical tasks, such as rehabilitation, could be performed with the use of modified commercial devices [2].

There are some metrics in the literature for performance evaluation of haptic devices that can be categorized into two sets [208]. One is the performance evaluation based on user studies, which is highly dependent on the application in which the haptic device is used. In these studies, some tasks are designed similar to the actual task in that intended application to be performed by human subjects, collect the data, analyze the data based on some measures such as task completion time, number of errors, the maximum force applied, quality of the task performed (by measuring the blood loss in surgical tasks, for example), and other relevant factors [209]. The results of that analysis can be used as a measure for the haptic device performance. Although this analysis and the corresponding results depend on the mechanism or kinematic design of the device, there is no direct or clear correlation between these two factors.

The second set of measures are more related to the physical characteristics and specification of the haptic device, such as workspace, manipulability, force generating capability, minimum controllable force (force resolution), maximum force, stability, low apparent inertia, low friction, back-drivability, redundancy, global positioning index, and many more factors [210]. To the best of the authors' knowledge, there is no systematic method proposed in the literature to optimize the mechanism design to meet a specific set of constraints. Most of these quantitative measures are highly application-dependent. For example, while higher force feedback capability might be very important in one application (e.g., in manufacturing dealing with high forces), it might not be as important in another application (e.g., in brain surgery dealing with low forces [211,212].

## 10. Current Challenges and Promising Future Directions

The design and development of haptic devices enabled many users to have a two-way interaction with machines. While they can be used to provide input commands (e.g., position or velocity commands for a surgical robotic system), they provide haptic or tactile feedback to the users' hands by pushing back on them and providing a sense of telepresence for the users. While visual or auditory sensory feedback can be considered the most important, haptic feedback provides an additional link to the users that can improve the quality of task performance. Despite many potential advantages of these devices, there have been many challenges in designing, developing, controlling, and adopting these devices in many applications.

The adoption of haptics technology has been very slow and many companies have been hesitating in incorporating this technology in their products. There is still an ongoing debate on the advantages and safety of such technologies in medical robotic systems. The interaction with hard objects such as bone tissue might introduce instability in the system. This problem becomes worse when there is a delay in the communication link between the local master haptic device and the remote follower robotic arm. There have been many efforts in addressing this issue by providing many control strategies such as the passivity approach, yet, it is still an open problem, and many researchers are providing new solutions.

Another challenge in adopting haptics technology in medical robotic systems is the acceptance of such technologies by healthcare providers, including surgeons. They might argue that the force feedback provided by these devices might distract them and limit their autonomy in performing delicate tasks in surgery. One possible solution to mitigate that problem is to provide high-quality surgical simulators and virtual reality systems for surgeons to compare their performance with and without haptic feedback. These simulators can potentially change their preference towards adopting haptics technology in their tools, such as robotic surgical systems.

The cost and complexity of haptic devices are also other challenges in this regard. The high cost of developing haptic devices causes the manufacturers and companies' hesitation in incorporating such devices in their products. There have been recent efforts in the development of high-quality and low-cost haptic devices. These efforts provide a promising future for haptic technologies by increasing the demand and decreasing manufacturing costs. In medical robotic systems, many major companies such as Intuitive Surgical, which commercializes the da Vinci Surgical System as the most popular robotic system in the world, are working on providing high-quality haptic feedback in their workstations for surgeons. As many patents of the da Vinci Surgical System are more than 20 years old and are expiring, other companies have made tremendous efforts in the design and development of new robotic surgical systems for medical communities to be used in different surgical and medical applications. One selling point of such novel systems can potentially be their workstation. The workstation of a medical robotic system is arguably the most integral part of the system as it connects the surgeon to the surgical site and tools. If misdesigned, it can degrade the quality of healthcare and cause complications. Ease of use, intuitiveness, and ergonomics are the main contributing factors. This workstation can be compared to its counterpart, the cockpit of an aircraft. The information provided to the surgeon by the workstation is used and processed by the surgeon to plan and execute the next move. Haptic feedback is arguably the most important sensory feedback after visual feedback. Surgeons rely on their judgment and their brains' high decision-making capability to make the next smart move. Every move in surgery can be the difference between life and death. Haptics technology can help surgeons to make a much more informed decision. This fact has been realized by many companies developing surgical robotic systems as a promising future direction.

## 11. Conclusion

Despite all efforts by design engineers, researchers, manufacturers, companies, knowledge users (e.g., surgeons), and others in the field of haptics concerning the design and development of novel haptic devices, there remains much work to do. This review paper shows the importance of this field for researchers and the possible gaps in the literature and knowledge. The kinematic design of various linkage-based haptic devices by researchers, which were explained in this paper, shows that there is no ideal haptic device that can be utilized for all or most applications. Each application, depending on the operator or end-user requirements, dictates the initial design of a new haptic device based on the experience of other designers. In medical applications, the most important factor is the acceptance and approval of the end-users (surgeons and healthcare providers), which in turn guarantees the success of the design. There are trade-offs between the desirable characteristics of haptic interfaces, such as maximum force feedback capability vs. minimum inertia or maximum stiffness vs. workspace size. Indeed, a large force feedback capability requires large actuators, which increases the HI's inertia. A large workspace requires long links, decreasing the HI's stiffness and increasing its inertia. Therefore, the design of haptic interfaces has to be optimized for a specific application. These design trade-offs can be relaxed by adding redundancy in the haptic interface mechanical design. Also, the kinematic and dynamic characteristics of redundant HIs can be further optimized through closed-loop control to reconfigure and adapt RHIs based on information about the task. This paper is an effort in providing a comprehensive review of linkage-based haptic devices for researchers and engineers and might help them in their design and development endeavors.

## Acknowledgments

This work was supported by Canada Foundation for Innovation (CFI), the Natural Sciences and Engineering Research Council (NSERC) of Canada, the Canadian Institutes of Health Research (CIHR), the Alberta Advanced Education Ministry, the Alberta Economic Development, and Trade and Tourism Ministry's grant to Centre for Autonomous Systems in Strengthening Future Communities.

## References

[1] Karon E. MacLean. Haptic interaction design for everyday interfaces. *Reviews of Human Factors and Ergonomics*, 4(1):149–194, 2008.

[2] Angel R Licona, Fei Liu, David Pinzon, Ali Torabi, Pierre Boulanger, Arnaud Lelevé, Richard Moreau, Minh Tu Pham, and Mahdi Tavakoli. Applications of haptics in medicine. *Haptic Interfaces for Accessibility, Health, and Enhanced Quality of Life*, pages 183–214, 2020.

[3] Evren Samur. *Performance metrics for haptic interfaces*. Springer Science & Business Media, 2012.

[4] Nima Enayati, Elena De Momi, and Giancarlo Ferrigno. Haptics in robot-assisted surgery: Challenges and benefits. *IEEE Reviews in Biomedical Engineering*, 9:49–65, 2016.

[5] P. S. Green, J. W. Hill, J. F. Jensen, and A. Shah. Telepresence surgery. *IEEE Engineering in Medicine and Biology Magazine*, 14(3):324–329, May 1995.

[6] Louis B. Rosenberg. Virtual fixtures: Perceptual tools for telerobotic manipulation. *Proceedings of IEEE Virtual Reality Annual International Symposium*, pages 76–82, 1993.

[7] Stuart A. Bowyer, Brian L. Davies, and Ferdinando Rodriguez y Baena. Active constraints/virtual fixtures: A survey. *IEEE Transactions on Robotics*, 30:138–157, 2014.

[8] Christian Hatzfeld and Thorsten A Kern. *Engineering Haptic Devices: A Beginner's Guide*. Springer London, 2014.

[9] Hasti Seifi, Farimah Fazlollahi, Michael Oppermann, John Andrew Sastrillo, Jessica Ip, Ashutosh Agrawal, Gunhyuk Park, Katherine J Kuchenbecker, and Karon E MacLean. Haptipedia: Accelerating haptic device discovery to support interaction & engineering design. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems*, pages 1–12, 2019.

[10] T. R. Coles, D. Meglan, and N. W. John. The role of haptics in medical training simulators: A survey of the state of the art. *IEEE Transactions on Haptics*, 4(1):51–66, January 2011.

[11] Alan Liu, Frank Tendick, Kevin Cleary, and Christoph Kaufmann. A survey of surgical simulation: Applications, technology, and education. *Presence: Teleoperators & Virtual Environments*, 12:599–614, 2003.

[12] Anthony G. Gallagher, Ellen M. Ritter, Howard R. Champion, Gerald Higgins, Marvin P. Fried, Gerald Moses, Calvin Douglas Smith, and Richard M. Satava. Virtual reality simulation for the operating room: proficiency-based training as a paradigm shift in surgical skills training. *Annals of surgery*, 241 2:364–72, 2005.

[13] Gabriel I. Barbash and Sherry Glied. New technology and health care costs–the case of robot-assisted surgery. *The New England journal of medicine*, 363 8:701–4, 2010.

[14] Christian Bolenz, Amit Gupta, Timothy D Hotze, Richard Ho, Jeffrey A. Cadeddu, Claus

Roehrborn, and Yair Lotan. Cost comparison of robotic, laparoscopic, and open radical prostatectomy for prostate cancer. *European urology*, 57 3:453–8, 2010.

[15] Gunnar Ahlberg, Lars Enochsson, Anthony G. Gallagher, Leif Hedman, Christian Hogman, David A. McClusky, Stig Ramel, C. Daniel Smith, and Dag Arvidsson. Proficiency-based virtual reality training significantly reduces the error rate for residents during their first 10 laparoscopic cholecystectomies. *The American Journal of Surgery*, 193(6):797 – 804, 2007.

[16] Michael Bajka, Stefan Tuchschmid, Matthias Streich, Daniel Fink, Gábor Székely, and Matthias Harders. Evaluation of a new virtual-reality training simulator for hysteroscopy. *Surgical endoscopy*, 23(9):2026, 2009.

[17] Thomas N Smyth and Arthur E Kirkpatrick. A new approach to haptic augmentation of the gui. In *Proceedings of the 8th international conference on Multimodal interfaces*, pages 372–379, 2006.

[18] Frederick P Brooks Jr, Ming Ouh-Young, James J Batter, and P Jerome Kilpatrick. Project gropehaptic displays for scientific visualization. *ACM SIGGraph computer graphics*, 24(4):177–185, 1990.

[19] Metin Sitti, Hideki Hashimoto, and O Kaynak. Teleoperated nano scale object manipulation. *Recent Advances on Mechatronics*, pages 322–335, 1999.

[20] William A McNeely, Kevin D Puterbaugh, and James J Troy. Six degree-of-freedom haptic rendering using voxel sampling. In *ACM SIGGRAPH 2005 Courses*, pages 42–es. Association for Computing Machinery (ACM), 2005.

[21] Scott L Delp, Peter Loan, Cagatay Basdogan, and Joseph M Rosen. Surgical simulation: An emerging technology for training in emergency medicine. *Presence: Teleoperators & Virtual Environments*, 6(2):147–159, 1997.

[22] Yoon Sang Kim, Jangwook Lee, Sooyong Lee, and Munsang Kim. A force reflected exoskeleton-type masterarm for human-robot interaction. *IEEE Transactions on Systems, Man, and Cybernetics-Part A: Systems and Humans*, 35(2):198–212, 2005.

[23] M Tavakoli, R. V. Patel, and M. Moallem. A haptic interface for computer-integrated endoscopic surgery and training. *Virtual Reality*, 9(2-3):160–176, 2006.

[24] A. Torabi, M. Khadem, K. Zareinia, G. R. Sutherland, and M. Tavakoli. Application of a redundant haptic interface in enhancing soft-tissue stiffness discrimination. *IEEE Robotics and Automation Letters*, 4(2):1037–1044, April 2019.

[25] A. Torabi, M. Khadem, K. Zareinia, G. R. Sutherland, and M. Tavakoli. Manipulability of teleoperated surgical robots with application in design of master/slave manipulators. In *2018 International Symposium on Medical Robotics (ISMR)*, pages 1–6, March 2018.

[26] M Bergamasco and CA Avizzano. Virtual environment technologies in rehabilitation. *Proc. of IEEE-RSJ-SICE Ro-Man*, 1997.

[27] H Igo Krebs, Neville Hogan, Mindy L Aisen, and Bruce T Volpe. Robot-aided neurorehabilitation. *IEEE transactions on rehabilitation engineering*, 6(1):75–87, 1998.

[28] Marcia K. O'Malley and Abhishek Gupta. Haptic interfaces. In Philip Kortum, editor, *HCI Beyond the GUI*, Interactive Technologies, pages 25 – 73. Morgan Kaufmann, San Francisco, 2008.

[29] Y. S. Kwoh, J. Hou, E. A. Jonckheere, and S. Hayati. A robot with improved absolute positioning accuracy for ct guided stereotactic brain surgery. *IEEE Transactions on Biomedical Engineering*, 35(2):153–160, Feb 1988.

[30] Hannes Götz Kenngott, L. Fischer, Felix Nickel, J Rom, Jens Rassweiler, and Beat P. Müller-Stich. Status of robotic assistance—a less traumatic and more accurate minimally invasive surgery? *Langenbeck's Archives of Surgery*, 397:333–341, 2011.

[31] Ming Han Lincoln Liow, Zhan Xia, Merng Koon Wong, Keng Jin Darren Tay, Seng Jin Yeo, and Pak Lin Chin. Robot-assisted total knee arthroplasty accurately restores the joint line and mechanical axis. a prospective randomised study. *The Journal of arthroplasty*, 29 12:2373–7, 2014.

[32] David Escobar-Castillejos, Julieta Noguez, Luis Neri, Alejandra Magana, and Bedrich Benes. A review of simulators with haptic devices for medical training. *Journal of medical systems*, 40(4):104, 2016.

[33] Tai Yonghang, Junsheng Shi, Lei Wei, Huang Xiaoqiao, Zaiqing Chen, and Qiong Li. Real-time visuo-haptic surgical simulator for medical education – a review. In *Recent Developments in Mechatronics and Intelligent Robotics, Proceedings of the International Conference on Mechatronics and Intelligent Robotics (ICMIR2017) – Volume 2*, pages 531–537, 05 2018.

[34] Armin Paul Mathias, Peter Vogel, and Markus Knauff. Different cognitive styles can affect performance in laparoscopic surgery skill training. *Surgical Endoscopy*, pages 1–8, 2019.

[35] Christopher J. Payne, Khushi Vyas, Daniel Bautista-Salinas, Dandan Zhang, Hani J. Marcus, and Guang-Zhong Yang. *Shared-Control Robots*, pages 63–79. Springer US, New York, NY, 2021.

[36] Soo-Chul Lim, Hyung-Kew Lee, and Joonah Park. Role of combined tactile and kinesthetic feedback in minimally invasive surgery. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 11(3):360–374, 2015.

[37] Lei Wei, Zoran Najdovski, Wael Abdelrahman, Saeid Nahavandi, and Harrison Weisinger. Augmented optometry training simulator with multi-point haptics. In *2012 IEEE International Conference on Systems, Man, and Cybernetics (SMC)*, pages 2991–2997. IEEE, 2012.

[38] Xiaojun Chen, Lin Yanping, Cheng-tao Wang, Guofang Shen, and Xudong Wang. A virtual training system using a force feedback haptic device for oral implantology. In *Lecture Notes in Computer Science*, volume 7220, pages 232–240, 01 2012.

[39] Ramesh Ramasamy, Mohamed Juhari, Masanori Sugisaka, and Noor Osman. Pneumatic artificial muscle in biomedical applications. In *3rd Kuala Lumpur International Conference on Biomedical Engineering 2006. IFMBE Proceedings*, pages 219–221. Springer, 01 2007.

[40] Ning Yi, Guo Xiao-jun, Li Xiao-ru, Xu Xiang-feng, and Ma Wan-jun. The implementation of haptic interaction in virtual surgery. In *2010 International Conference on Electrical and Control Engineering*, pages 2351–2354. IEEE, 2010.

[41] Arianna Saracino, Timo JC Oude-Vrielink, Arianna Menciassi, Edoardo Sinibaldi, and George P Mylonas. Haptic intracorporeal palpation using a cable-driven parallel robot: a user study. *IEEE Transactions on Biomedical Engineering*, 67(12):3452–3463, 2020.

[42] Arianna Saracino, Anton Deguet, Fabio Staderini, Mohamed Nassim Boushaki, Fabio Cianchi, Arianna Menciassi, and Edoardo Sinibaldi. Haptic feedback in the da vinci research kit (dvrk): a user study based on grasping, palpation, and incision tasks. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 15(4):e1999, 2019.

[43] R. Hui, A. Ouellet, A. Wang, P. Kry, S. Williams, G. Vukovich, and W. Peruzzini. Mechanisms for haptic feedback. In *Proceedings of 1995 IEEE International Conference on Robotics and Automation*, volume 2, pages 2138–2143 vol.2, May 1995.

[44] Mahdi Tavakoli, Arash Aziminejad, Rajni V Patel, and Mehrdad Moallem. High-fidelity bilateral teleoperation systems and the effect of multimodal haptics. *IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics)*, 37(6):1512–1528, 2007.

[45] Marcia K O'Malley and Robert O Ambrose. Haptic feedback applications for robonaut. *Industrial Robot: An International Journal*, 2003.

[46] Lorraine EP Williams, R Bowen Loftin, Hal A Aldridge, Ernst L Leiss, and William J Bluethmann. Kinesthetic and visual force display for telerobotics. In *Proceedings 2002 IEEE international conference on robotics and automation (Cat. No. 02CH37292)*, volume 2, pages 1249–1254. IEEE, 2002.

[47] Peter Berkelman and Ji Ma. A compact modular teleoperated robotic system for laparoscopic surgery. *The International Journal of Robotics Research*, 28(9):1198–1215, 2009.

[48] Kelly S Hale and Kay M Stanney. Deriving haptic design guidelines from human physiological, psychophysical, and neurological foundations. *IEEE computer graphics and applications*, 24(2):33–39, 2004.

[49] Gianni Campion and Vincent Hayward. Fundamental limits in the rendering of virtual haptic textures. In *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*, pages 263–270. IEEE, 2005.

[50] Kevin C Olds. Global indices for kinematic and force transmission performance in parallel robots. *IEEE Transactions on Robotics*, 31(2):494–500, 2015.

[51] J. P. Merlet. Jacobian, Manipulability, Condition Number, and Accuracy of Parallel Robots. *Journal of Mechanical Design*, 128(1):199–206, 06 2005.

[52] Grigore Gogu. Fully-isotropic parallel mechanisms-an innovative concept for haptic devices. In *Product Engineering*, pages 169–194. Springer, 2008.

[53] Xuan Sun. *A methodology for situated and effective design of haptic devices.* PhD thesis, KTH Royal Institute of Technology, 2017.

[54] Abdulmotaleb El Saddik, Mauricio Orozco, Mohamad Eid, and Jongeun Cha. *Haptics technologies: bringing touch to multimedia.* Springer Science & Business Media, 2011.

[55] Vincent Hayward and Oliver R Astley. Performance Measures for Haptic Interfaces. *International Symposium In Robotics Research*, 1:195–207, 1996.

[56] R.E. Ellis, O.M. Ismaeil, and M.G. Lipsett. Design and evaluation of a high-performance haptic interface. *Robotica*, 14(03):321, 1996.

[57] Thomas H. Massie and J. K. Salisbury. The phantom haptic interface: A device for probing virtual objects. In *Proceedings of the ASME Dynamic Systems and Control Division*, pages 295–301, 1994.

[58] Mandayam A Srinivasan and Cagatay Basdogan. Haptics in virtual environments: Taxonomy, research status, and challenges. *Computers & Graphics*, 21(4):393–404, 1997.

[59] Tsuneo Yoshikawa. Manipulability of Robotic Mechanisms. *The International Journal of Robotics Research*, 4(2):3–9, 1985.

[60] Javier Martin and Joan Savall. Mechanisms for haptic torque feedback. In *First Joint Eurohaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems. World Haptics Conference*, pages 611–614. IEEE, 2005.

[61] Han Sung Kim. Mechanism design of haptic devices. *Advances in Haptics*, pages 283–298, 2010.

[62] L. Stocco and S.E. E Salcudean. A Coarse-Fine approach to force-reflecting hand controller design. In *Proceedings of IEEE International Conference on Robotics and Automation*, volume 1996, pages 404–410, 1996.

[63] D. A. Lawrence and J. D. Chapel. Performance trade-offs for hand controller design. In *Proceedings of the 1994 IEEE International Conference on Robotics and Automation*, pages 3211–3216 vol.4, May 1994.

[64] A. Gupta and M. K. O'Malley. Design of a haptic arm exoskeleton for training and rehabilitation. *IEEE/ASME Transactions on Mechatronics*, 11(3):280–289, June 2006.

[65] Marc Ueberle, Nico Mock, and Martin Buss. Design, control, and evaluation of a hyper-redundant haptic device. In *Advances in Telerobotics*, pages 25–44. Springer, 2007.

[66] Touch$^{\mathrm{TM}}$. https://www.3dsystems.com/haptics-devices/touch. Accessed: 2020-09-30.

[67] Touch X$^{\mathrm{TM}}$. https://www.3dsystems.com/haptics-devices/touch-x. Accessed: 2020-09-30.

[68] Phantom Premium$^{\mathrm{TM}}$. https://www.3dsystems.com/haptics-devices/3d-systems-phantom-premium. Accessed: 2020-09-30.

[69] Virtuose$^{\mathrm{TM}}$ 3D Desktop. https://www.haption.com/en/products-en/virtuose-3d-desktop-en.html. Accessed: 2020-09-30.

[70] Virtuose$^{\mathrm{TM}}$ 3D. https://www.haption.com/en/products-en/virtuose-3d-en.html. Accessed: 2020-09-30.

[71] Virtuose$^{\mathrm{TM}}$ 6D Desktop. https://www.haption.com/en/products-en/virtuose-6d-desktop-en.html. Accessed: 2020-09-30.

[72] Virtuose$^{\mathrm{TM}}$ 6D. https://www.haption.com/en/products-en/virtuose-6d-en.html. Accessed: 2020-09-30.

[73] Virtuose$^{TM}$ 6D TAO. https://www.haption.com/en/products-en/virtuose-6d-tao-en.html. Accessed: 2020-09-30.

[74] Vincent Hayward, Pedro Gregorio, O Astley, Stephanie Greenish, Michel Doyon, L Lessard, John McDougall, Ian Sinclair, S Boelen, X Chen, and Others. Freedom-7: A high fidelity seven axis haptic device with application to surgical training. In *Experimental Robotics V*, pages 443–456. Springer, 1998.

[75] M. Ueberle and M. Buss. Design, control, and evaluation of a new 6 dof haptic device. In *IEEE/RSJ International Conference on Intelligent Robots and Systems*, volume 3, pages 2949–2954 vol.3, Sep. 2002.

[76] Richard Q Van der Linde, Piet Lammertse, Erwin Frederiksen, and B Ruiter. The hapticmaster, a new high-performance haptic interface. In *Proc. Eurohaptics*, pages 1–5, 2002.

[77] Force Dimension Omega.x. https://www.forcedimension.com/products/omega. Accessed: 2020-09-30.

[78] Force Dimension Delta. https://www.forcedimension.com/products/delta. Accessed: 2020-09-30.

[79] Force Dimension sigma.7. https://www.forcedimension.com/products/sigma. Accessed: 2020-09-30.

[80] HD$^2$ High Definition Haptic Device. https://www.quanser.com/products/hd2-high-definition-haptic-device/. Accessed: 2020-09-30.

[81] Sajeeva Abeywardena and Chao Chen. Implementation and evaluation of a three-legged six-degrees-of-freedom parallel mechanism as an impedance-type haptic device. *IEEE/ASME Transactions on Mechatronics*, 22(3):1412–1422, 2017.

[82] Marc Ueberle, Nico Mock, and Martin Buss. VISHARD10, a novel hyper-redundant haptic interface. In *Proceedings - 12th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, HAPTICS*, pages 58–65, 2004.

[83] Yuichi Tsumaki, Hitoshi Naruse, Dragomir N Nenchev, and Masaru Uchiyama. Design of a compact 6-dof haptic interface. In *Proceedings. 1998 IEEE International Conference on Robotics and Automation (Cat. No. 98CH36146)*, volume 3, pages 2580–2585. IEEE, 1998.

[84] J-GS Demers, JMA Boelen, and IPW Sinclair. Freedom 6S force feedback hand controller. *IFAC Proceedings Volumes*, 31(33):115–120, 1998.

[85] Cybergrasp. http://www.cyberglovesystems.com/cybergrasp. Accessed: 2020-09-30.

[86] Cyberforce. http://www.cyberglovesystems.com/cyberforce. Accessed: 2020-09-30.

[87] Lionel Birglen, Clément Gosselin, Nicolas Pouliot, Bruno Monsarrat, and Thierry Laliberté. Shade, a new 3-dof haptic device. *IEEE Transactions on Robotics and Automation*, 18(2):166–175, 2002.

[88] Gareth Barnaby and Anne Roudaut. Mantis: A scalable, lightweight and accessible architecture to build multiform force feedback systems. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, pages 937–948, 2019.

[89] A L Trejos, R V Patel, and M D Naish. Force sensing and its application in minimally invasive surgery and therapy: A survey. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 224(7):1435–1454, 2010.

[90] M Lazeroms, G Villavicencio, W Jongkind, and G Honderd. Optical fibre force sensor for minimal-invasive-surgery grasping instruments. In *Proceedings of 18th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, volume 1, pages 234–235. IEEE, 1996.

[91] Hong Z Tan, Xiao Dong Pang, Nathaniel I Durlach, et al. Manual resolution of length, force, and compliance. *Advances in Robotics*, 42:13–18, 1992.

[92] Hong Z Tan, Mandayam A Srinivasan, Brian Eberman, and Belinda Cheng. Human factors for the design of force-reflecting haptic interfaces. *Dynamic Systems and Control*, 55(1):353–359, 1994.

[93] M. C. Çavuşoğlu, D. Feygin, and F. Tendick. A critical study of the mechanical and electrical

properties of the phantom haptic interface and improvements for highperformance control. *Presence: Teleoperators and Virtual Environments*, 11(6):555–568, Dec 2002.

[94] Jonas Forsslund, Michael Yip, and Eva-Lotta Sallnäs. Woodenhaptics: A starting kit for crafting force-reflecting spatial haptic devices. In *Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, TEI '15, page 133–140, New York, NY, USA, 2015. Association for Computing Machinery.

[95] V. Hayward, P. Gregorio, O. Astley, S. Greenish, M. Doyon, L. Lessard, J. McDougall, I. Sinclair, S. Boelen, X. Chen, J.-G. Demers, J. Poulin, I. Benguigui, N. Almey, B. Makuc, and X. Zhang. Freedom-7: A high fidelity seven axis haptic device with application to surgical training. In Alicia Casals and Anibal T. de Almeida, editors, *Experimental Robotics V*, pages 443–456, Berlin, Heidelberg, 1998. Springer Berlin Heidelberg.

[96] A. Sledd and M. K. O'Malley. Performance enhancement of a haptic arm exoskeleton. In *2006 14th Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems*, pages 375–381, March 2006.

[97] Mahya Shahbazi, S Farokh Atashzar, Mahdi Tavakoli, and Rajni V Patel. Therapist-in-the-loop robotics-assisted mirror rehabilitation therapy: An assist-as-needed framework. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pages 5910–5915. IEEE, 2015.

[98] Richard Q Van der Linde, Piet Lammertse, Erwin Frederiksen, and B Ruiter. The hapticmaster, a new high-performance haptic interface. In *Proc. Eurohaptics*, pages 1–5, 2002.

[99] R.Q. van der Linde and P. Lammertse. Hapticmaster – a generic force controlled robot for human interaction. *Industrial Robot: the international journal of robotics research and application*, 30(6):515–524, 2003.

[100] Richard J Adams and Blake Hannaford. Control law design for haptic interfaces to virtual reality. *IEEE Transactions on control systems technology*, 10(1):3–13, 2002.

[101] Leo J. Stocco, Septimiu E. Salcudean, and Farrokh Sassani. Optimal kinematic design of a haptic pen. *IEEE/ASME Transactions on Mechatronics*, 6(3):210–220, 2001.

[102] Sébastien Grange, François Conti, P Rouiller, P Helmer, and Charles Baur. The delta haptic device. *Mecatronics*, 2001.

[103] Andreas Tobergte, Patrick Helmer, Ulrich Hagn, Patrice Rouiller, Sophie Thielmann, Sébastien Grange, Alin Albu-Schäffer, François Conti, and Gerd Hirzinger. The sigma. 7 haptic interface for mirosurge: A new bi-manual surgical console. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 3023–3030. IEEE, 2011.

[104] Haruhiko Asada and Kamal Youcef-Toumi. Analysis and Design of a Direct-Drive Arm With a Five-Bar-Link Parallel Drive Mechanism. *Journal of Dynamic Systems, Measurement, and Control*, 106(3):225–230, 09 1984.

[105] Reymond Clavel. Device for the movement and positioning of an element in space, December 11 1990. US Patent 4,976,582.

[106] Peter Vischer and Reymond Clavel. Kinematic calibration of the parallel delta robot. *Robotica*, 16(2):207–218, 1998.

[107] Vincent Hayward. Toward a seven axis haptic device. In *Proceedings 1995 IEEE/RSJ International Conference on Intelligent Robots and Systems. Human Robot Interaction and Cooperative Robots*, volume 3, pages 133–139. IEEE, 1995.

[108] Lung-Wen Tsai and Sameer Joshi. Kinematic analysis of 3-dof position mechanisms for use in hybrid kinematic machines. *J. Mech. Des.*, 124(2):245–253, 2002.

[109] Damien Chablat and Philippe Wenger. A six degree-of-freedom haptic device based on the orthoglide and a hybrid agile eye. In *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, volume 42568, pages 795–802, 2006.

[110] Yong Li, Zhiyuan Yan, Hongmin Wang, Zhijiang Du, and Yuchun Zhang. Design and optimization of a haptic manipulator using series-parallel mechanism. In *2012 IEEE International Conference on Mechatronics and Automation*, pages 2140–2145. IEEE, 2012.

[111] Clément M Gosselin and J-F Hamel. The agile eye: a high-performance three-degree-of-freedom camera-orienting device. In *Proceedings of the 1994 IEEE international conference on robotics and automation*, pages 781–786. IEEE, 1994.

[112] Mehmet İsmet Can Dede, Özgün Selvi, Tunç Bilgincan, and Yalkin Kant. Design of a haptic device for teleoperation and virtual reality systems. In *2009 IEEE International Conference on Systems, Man and Cybernetics*, pages 3623–3628. IEEE, 2009.

[113] Garnette R Sutherland, Stefan Wolfsberger, Sanju Lama, and Kourosh Zarei-nia. The evolution of neuroarm. *Neurosurgery*, 72(suppl_1):A27–A32, 2013.

[114] H Jex. Four critical tests for control-feel simulators. In *23rd Annual Conference on Manual Control*, 1988.

[115] D. A. McAffee and P. Fiorini. Hand controller design requirements and performance issues in telerobotics. In *Fifth International Conference on Advanced Robotics 'Robots in Unstructured Environments*, pages 186–192 vol.1, June 1991.

[116] Ian W Hunter, John M Hollerbach, and John Ballantyne. A comparative analysis of actuator technologies for robotics. *Robotics Review*, 2:299–342, 1991.

[117] John B. Morrell and J. Kenneth Salisbury. Parallel-coupled micro-macro actuators. *The International Journal of Robotics Research*, 17(7):773–791, 1998.

[118] A. Kumar and K. J. Waldron. The Workspaces of a Mechanical Manipulator. *Journal of Mechanical Design*, 103(3):665–672, 07 1981.

[119] D. C. H. Yang and T. W. Lee. On the Workspace of Mechanical Manipulators. *Journal of Mechanisms, Transmissions, and Automation in Design*, 105(1):62–69, 03 1983.

[120] Y. C. Tsai and A. H. Soni. An Algorithm for the Workspace of a General n-R Robot. *Journal of Mechanisms, Transmissions, and Automation in Design*, 105(1):52–57, 03 1983.

[121] K. C. Gupta and B. Roth. Design Considerations for Manipulator Workspace. *Journal of Mechanical Design*, 104(4):704–711, 10 1982.

[122] K.C. Gupta. On the nature of robot workspace. *The International Journal of Robotics Research*, 5(2):112–121, 1986.

[123] F. Freudenstein and E. J. F. Primrose. On the Analysis and Synthesis of the Workspace of a Three-Link, Turning-Pair Connected Robot Arm. *Journal of Mechanisms, Transmissions, and Automation in Design*, 106(3):365–370, 09 1984.

[124] Chih-Chung Daniel Lin and Ferdinand Freudenstein. Optimization of the workspace of a three-link turning-pair connected robot arm. *The International journal of robotics research*, 5(2):104–110, 1986.

[125] R Vijaykumar, KJ Waldron, and MJ Tsai. Geometric optimization of serial chain manipulator structures for working volume and dexterity. *The International Journal of Robotics Research*, 5(2):91–103, 1986.

[126] J Kenneth Salisbury and John J Craig. Articulated Hands: Force Control and Kinematic Issues. *The International Journal of Robotics Research*, 1(1):4–17, 1982.

[127] C. Gosselin and J. Angeles. A Global Performance Index for the Kinematic Optimization of Robotic Manipulators. *Journal of Mechanical Design*, 113:220, 1991.

[128] Han Sung Kim and Lung-Wen Tsai. Design optimization of a cartesian parallel manipulator. *J. Mech. Des.*, 125(1):43–51, 2003.

[129] Jungwon Yoon and Jeha Ryu. Design, fabrication, and evaluation of a new haptic device using a parallel mechanism. *IEEE/ASME Transactions on mechatronics*, 6(3):221–233, 2001.

[130] Haruhiko Asada. A Geometrical Representation of Manipulator Dynamics and Its Application to Arm Design. *Journal of Dynamic Systems, Measurement, and Control*, 105(3):131–142, 09 1983.

[131] Oussama Khatib. Inertial Properties in Robotic Manipulation: An Object Level Framework. *International Journal Of Robotics Research*, 13(1):19–36, 1995.

[132] Mahdi Tavakoli, Rajni V. Patel, and Mehrdad Moallem. Design issues in a haptics-based master-slave system for minimally invasive surgery. In *IEEE International Conference on Robotics and*

*Automation, 2004. Proceedings. ICRA'04. 2004*, volume 1, pages 371–376. IEEE, 2004.

[133] Han S Kim and Yong J Choi. Forward/inverse force transmission capability analyses of fully parallel manipulators. *IEEE Transactions on Robotics and Automation*, 17(4):526–531, 2001.

[134] Bruno Siciliano. Kinematic control of redundant robot manipulators: A tutorial. *Journal of Intelligent and Robotic Systems*, 3(3):201–212, 1990.

[135] Matjaž Mihelj. Human arm kinematics for robot based rehabilitation. *Robotica*, 24(3):377–383, 2006.

[136] Stefan Schaal and Nicolas Schweighofer. Computational motor control in humans and robots. *Current Opinion in Neurobiology*, 15(6):675 – 682, 2005. Motor sytems / Neurobiology of behaviour.

[137] Ilana Nisky, Michael H. Hsieh, and Allison M. Okamura. Uncontrolled manifold analysis of arm joint angle variability during robotic teleoperation and freehand movement of surgeons and novices. *IEEE Transactions on Biomedical Engineering*, 61(12):2869–2881, dec 2014.

[138] Stefano Chiaverini, Giuseppe Oriolo, and Anthony A. Maciejewski. Redundant robots. In Bruno Siciliano and Oussama Khatib, editors, *Springer Handbook of Robotics*, pages 221–242. Springer International Publishing, Cham, 2016.

[139] Fanny Ficuciello, Luigi Villani, and Bruno Siciliano. Variable impedance control of redundant manipulators for intuitive human – robot physical interaction. *Transactions on Robotics*, 31(4):1–14, 2015.

[140] J Kenneth Salisbury Jr, Akhil J Madhani, Gary S Guthart, Gunter D Niemeyer, and Eugene F Duval. Master having redundant degrees of freedom, 2004. US Patent 6,684,129.

[141] Ali Torabi, Mohsen Khadem, Koroush Zareinia, Garnette Roy Sutherland, and Mahdi Tavakoli. Using a redundant user interface in teleoperated surgical systems for task performance enhancement. *Robotica*, page 1–15, 2020.

[142] Ozgur Baser, E Ilhan Konukseven, and Tuna Balkan. Optimal posture control for a 7 dof haptic device based on power minimization. In *International Conference on Human Haptic Sensing and Touch Enabled Computer Applications*, pages 555–560. Springer, 2008.

[143] ÖZGÜR BAŞER and Erhan Ilhan Konukseven. 7-dof haptic device and interface design. *Turkish Journal of Electrical Engineering & Computer Sciences*, 21(2):493–499, 2013.

[144] Alastair Barrow and William Harwin. Design and analysis of a haptic device design for large and fast movements. *Machines*, 4(1):1–19, 2016.

[145] Han Sung Kim. Kinematically redundant parallel haptic device with large workspace. *International Journal of Advanced Robotic Systems*, 9(6):260, 2012.

[146] F. Gosselin, C. Andriot, F. Bergez, and X. Merlhiot. Widening 6-dof haptic devices workspace with an additional degree of freedom. In *Second Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (WHC'07)*, pages 452–457, March 2007.

[147] Nitendra Nath, Enver Tatlicioglu, and Darren M. Dawson. Teleoperation with kinematically redundant robot manipulators with sub-task objectives. *Robotica*, 27:1027–1038, 2009.

[148] Clément Gosselin and Louis-Thomas Schreiber. Redundancy in Parallel Mechanisms: A Review. *Applied Mechanics Reviews*, 70(1), 01 2018. 010802.

[149] Patrice Lambert and Just L. Herder. A 7-dof redundantly actuated parallel haptic device combining 6-dof manipulation and 1-dof grasping. *Mechanism and Machine Theory*, 134:349 – 364, 2019.

[150] D. Constantinescu, I. Chau, S. P. DiMaio, L. Filipozzi, S. E. Salcudean, and F. Ghassemi. Haptic rendering of planar rigid-body motion using a redundant parallel mechanism. In *Proceedings 2000 ICRA. Millennium Conference. IEEE International Conference on Robotics and Automation. Symposia Proceedings (Cat. No.00CH37065)*, volume 3, pages 2440–2445 vol.3, April 2000.

[151] Pietro Buttolo and Blake Hannaford. Advantages of actuation redundancy for the design of haptic displays. In *Proceedings ASME Fourth Annual Symposium on Haptic Interfaces for*

*Virtual Environment and Teleoperator Systems.*, pages 1–8, 1995.

[152] Jumpei Arata, Hiroyuki Kondo, Norio Ikedo, and Hideo Fujimoto. Haptic device using a newly developed redundant parallel mechanism. *IEEE Transactions on robotics*, 27(2):201–214, 2011.

[153] Kris Hauser and Scott Emmons. Global redundancy resolution via continuous pseudoinversion of the forward kinematic map. *IEEE Transactions on Automation Science and Engineering*, 15(3):932–944, 2018.

[154] Alessandro De Luca and Giuseppe Oriolo. The reduced gradient method for solving redundancy in robot arms. *Robotersysteme*, 7(2):117–122, 1991.

[155] Yoshihiko Nakamura and Hideo Hanafusa. Inverse Kinematic Solutions With Singularity Robustness for Robot Manipulator Control. *Journal of Dynamic Systems, Measurement, and Control*, 108(3):163, sep 1986.

[156] Tan Fung Chan and Rajiv V Dubey. A weighted least-norm solution based scheme for avoiding joint limits for redundant joint manipulators. *IEEE Transactions on Robotics and Automation*, 11(2):286–292, 1995.

[157] Masahide Ito, Kazuyoshi Kawatsu, and Masaaki Shibata. Kinematic control of redundant manipulators for admitting joint range of motion maximally. *IEEJ Journal of Industry Applications*, 6(4):278–285, 2017.

[158] Bernard Bayle, J-Y Fourquet, and Marc Renaud. Manipulability of wheeled mobile manipulators: Application to motion generation. *The International Journal of Robotics Research*, 22(7-8):565–581, 2003.

[159] Ping Hsu, John Mauser, and Shankar Sastry. Dynamic control of redundant manipulators. *Journal of Robotic Systems*, 6(2):133–148, 1989.

[160] A. Torabi, K. Zareinia, G. R. Sutherland, and M. Tavakoli. Dynamic reconfiguration of redundant haptic interfaces for rendering soft and hard contacts. *IEEE Transactions on Haptics*, pages 1–1, 2020.

[161] A. Torabi, K. Zareinia, G. R. Sutherland, and M. Tavakoli. Redundant haptic interfaces for enhanced force feedback capability despite joint torque limits. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)*, pages 1–7, 2020.

[162] Darwin G Caldwell and Clarence Gosney. Enhanced tactile feedback (tele-taction) using a multi-functional sensory system. In *[1993] Proceedings IEEE International Conference on Robotics and Automation*, pages 955–960. IEEE, 1993.

[163] Hwan Kim, Minhwan Kim, and Woohun Lee. Hapthimble: A wearable haptic device towards usable virtual touch screen. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, pages 3694–3705, 2016.

[164] Inrak Choi, Heather Culbertson, Mark R Miller, Alex Olwal, and Sean Follmer. Grabity: A wearable haptic interface for simulating weight and grasping in virtual reality. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology*, pages 119–130, 2017.

[165] Vibol Yem and Hiroyuki Kajimoto. Wearable tactile device using mechanical and electrical stimulation for fingertip interaction with virtual world. In *2017 IEEE Virtual Reality (VR)*, pages 99–104. IEEE, 2017.

[166] Fabrizio Pece, Juan Jose Zarate, Velko Vechev, Nadine Besse, Olexandr Gudozhnik, Herbert Shea, and Otmar Hilliges. Magtics: Flexible and thin form factor magnetic actuators for dynamic and wearable haptic feedback. In *Proceedings of the 30th annual ACM symposium on User interface software and technology*, pages 143–154, 2017.

[167] Rongjia Tao and Gabriel D Roy. *Electrorheological fluids: mechanisms, properties, technology, and applications.* World Scientific, 1994.

[168] Young-Min Han and Seung-Bok Choi. Force-feedback control of a spherical haptic device featuring an electrorheological fluid. *Smart materials and structures*, 15(5):1438, 2006.

[169] Scott H Winter and Mourad Bouzit. Use of magnetorheological fluid in a force feedback glove. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 15(1):2–8, 2007.

[170] Hugh Boys, Gabriele Frediani, Stefan Poslad, James Busfield, and Federico Carpi. A dielectric elastomer actuator-based tactile display for multiple fingertip interaction with virtual soft bodies. In *Electroactive Polymer Actuators and Devices (EAPAD) 2017*, volume 10163, page 101632D. International Society for Optics and Photonics, 2017.

[171] Ferdinando Auricchio, Robert L Taylor, and Jacob Lubliner. Shape-memory alloys: macromodelling and numerical simulations of the superelastic behavior. *Computer methods in applied mechanics and engineering*, 146(3-4):281–312, 1997.

[172] Harald Staab, Arne Sonnenburg, and Christof Hieger. The dohelix-muscle: A novel technical muscle for bionic robots and actuating drive applications. In *2007 IEEE International Conference on Automation Science and Engineering*, pages 306–311. IEEE, 2007.

[173] Chang Liu and Yoseph Bar-Cohen. Scaling laws of microactuators and potential applications of electroactive polymers in mems. In *Smart Structures and Materials 1999: Electroactive Polymer Actuators and Devices*, volume 3669, pages 345–354. International Society for Optics and Photonics, 1999.

[174] Bogdan Vigaru, James Sulzer, and Roger Gassert. Design and evaluation of a cable-driven fmri-compatible haptic interface to investigate precision grip control. *IEEE transactions on haptics*, 9(1):20–32, 2015.

[175] Carlo Alberto Avizzano, Massimo Satler, and Emanuele Ruffaldi. Portable haptic interface with omni-directional movement and force capability. *IEEE transactions on haptics*, 7(2):110–120, 2014.

[176] Maglev Haptics. https://butterflyhaptics.com/maglev-haptics/. Accessed: 2021-03-10.

[177] RL Hollis and AP Allan. A magnetically levitated fine motion wrist: Design and feasibility experiments. In *ASME Winter Annual Meeting*, 1988.

[178] S Salcudean and Ralph L Hollis. A magnetically levitated fine motion wrist: Kinematics, dynamics and control. In *Proceedings. 1988 IEEE International Conference on Robotics and Automation*, pages 261–266. IEEE, 1988.

[179] RL Hollis, AP Allan, and S Salcudean. A six degree-of-freedom magnetically levitated variable compliance fine motion wrist. In *Proceedings of the 4th international symposium on Robotics Research*, pages 65–73, 1988.

[180] Ralph L Hollis Jr. Magnetically levitated fine motion robot wrist with programmable compliance, October 17 1989. US Patent 4,874,998.

[181] Septimiu E Salcudean, NM Wong, and Ralph L Hollis. A force-reflecting teleoperation system with magnetically levitated master and wrist. In *Proceedings 1992 IEEE International Conference on Robotics and Automation*, pages 1420–1426. IEEE, 1992.

[182] Ralph L Hollis Jr and Septimiu E Salcudean. Input/output system for computer user interface using magnetic levitation, September 8 1992. US Patent 5,146,566.

[183] Peter J Berkelman, Zack J Butler, and Ralph L Hollis. Design of a hemispherical magnetic levitation haptic interface device. In *Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems,(Atlanta)*, volume 58, pages 483–488. Citeseer, 1996.

[184] Peter Berkelman and Ralph L Hollis. Dynamic performance of a magnetic levitation haptic device. In *Telemanipulator and Telepresence Technologies IV*, volume 3206, pages 140–149. International Society for Optics and Photonics, 1997.

[185] Bertram Unger and Ralph Hollis. Design and operation of a force-reflecting magnetic levitation coarse-fine teleoperation system. In *IEEE International Conference on Robotics and Automation, 2004. Proceedings. ICRA'04. 2004*, volume 4, pages 4147–4152. IEEE, 2004.

[186] BJ Unger, Roberta L Klatzky, and Ralph L Hollis. Teleoperation mediated through magnetic levitation: Recent results. *Proceedings of IEEE Mechatronics & Robotics (MechRob'04), Special Session on Telepresence and Teleaction*, pages 1458–1462, 2004.

[187] Ralph Hollis. Maglev haptics: butterfly haptic's new user interface technology. In *ACM SIGGRAPH 2008 new tech demos*, pages 1–1. Association for Computing Machinery (ACM),

2008.

[188] Ralph LeRoy Hollis et al. Magnetic levitation haptic interface system, July 30 2013. US Patent 8,497,767.

[189] Massimiliano Gabardi, Massimiliano Solazzi, Daniele Leonardis, and Antonio Frisoli. A new wearable fingertip haptic interface for the rendering of virtual shapes and surface features. In *2016 IEEE Haptics Symposium (HAPTICS)*, pages 140–146. IEEE, 2016.

[190] Claudio Pacchierotti, Gionata Salvietti, Irfan Hussain, Leonardo Meli, and Domenico Prattichizzo. The hring: A wearable haptic device to avoid occlusions in hand tracking. In *2016 IEEE Haptics Symposium (HAPTICS)*, pages 134–139. IEEE, 2016.

[191] Dzmitry Tsetserukou, Shotaro Hosokawa, and Kazuhiko Terashima. Linktouch: A wearable haptic device with five-bar linkage mechanism for presentation of two-dof force feedback at the fingerpad. In *2014 IEEE Haptics Symposium (HAPTICS)*, pages 307–312. IEEE, 2014.

[192] Claudio Pacchierotti, Stephen Sinclair, Massimiliano Solazzi, Antonio Frisoli, Vincent Hayward, and Domenico Prattichizzo. Wearable haptic systems for the fingertip and the hand: taxonomy, review, and perspectives. *IEEE transactions on haptics*, 10(4):580–600, 2017.

[193] Jérôme Perret and Emmanuel Vander Poorten. Touching virtual reality: a review of haptic gloves. In *ACTUATOR 2018; 16th International Conference on New Actuators*, pages 1–5. VDE, 2018.

[194] Leonardo Meli, Irfan Hussain, Mirko Aurilio, Monica Malvezzi, Marcia K O'Malley, and Domenico Prattichizzo. The hbracelet: a wearable haptic device for the distributed mechanotactile stimulation of the upper limb. *IEEE Robotics and Automation Letters*, 3(3):2198–2205, 2018.

[195] Nathaniel Agharese, Tyler Cloyd, Laura H Blumenschein, Michael Raitor, Elliot W Hawkes, Heather Culbertson, and Allison M Okamura. Hapwrap: Soft growing wearable haptic device. In *2018 IEEE International Conference on Robotics and Automation (ICRA)*, pages 5466–5472. IEEE, 2018.

[196] Matteo Rossi, Matteo Bianchi, Edoardo Battaglia, Manuel G Catalano, and Antonio Bicchi. Happro: a wearable haptic device for proprioceptive feedback. *IEEE Transactions on Biomedical Engineering*, 66(1):138–149, 2018.

[197] Inrak Choi, Elliot W Hawkes, David L Christensen, Christopher J Ploch, and Sean Follmer. Wolverine: A wearable haptic interface for grasping in virtual reality. In *2016 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 986–993. IEEE, 2016.

[198] Ronan Hinchet, Velko Vechev, Herbert Shea, and Otmar Hilliges. Dextres: Wearable haptic feedback for grasping in vr via a thin form-factor electrostatic brake. In *Proceedings of the 31st Annual ACM Symposium on User Interface Software and Technology*, pages 901–912, 2018.

[199] Mohssen Hosseini, Ali Sengül, Yudha Pane, Joris De Schutter, and Herman Bruyninck. Exoten-glove: A force-feedback haptic glove based on twisted string actuation system. In *2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN)*, pages 320–327. IEEE, 2018.

[200] MA Zhou and Pinhas Ben-Tzvi. Rml glove—an exoskeleton glove mechanism with haptics feedback. *IEEE/Asme Transactions on mechatronics*, 20(2):641–652, 2014.

[201] Swagata Das, Yusuke Kishishita, Toshio Tsuji, Cassie Lowell, Kazunori Ogawa, and Yuichi Kurita. Forcehand glove: a wearable force-feedback glove with pneumatic artificial muscles (pams). *IEEE Robotics and Automation Letters*, 3(3):2416–2423, 2018.

[202] Oliver Ozioko, William Navaraj, Marion Hersh, and Ravinder Dahiya. Tacsac: A wearable haptic device with capacitive touch-sensing capability for tactile display. *Sensors*, 20(17):4780, 2020.

[203] Yeongyu Park, Inseong Jo, Jeongsoo Lee, and Joonbum Bae. Wehaptic: A wearable haptic interface for accurate position tracking and interactive force control. *Mechanism and Machine Theory*, 153:104005, 2020.

[204] Vijay Rajanna, Patrick Vo, Jerry Barth, Matthew Mjelde, Trevor Grey, Cassandra Oduola, and Tracy Hammond. Kinohaptics: An automated, wearable, haptic assisted, physio-therapeutic

system for post-surgery rehabilitation and self-care. *Journal of medical systems*, 40(3):60, 2016.

[205] Antonella Mazzoni and Nick Bryan-Kinns. Mood glove: A haptic wearable prototype system to enhance mood music in film. *Entertainment Computing*, 17:9–17, 2016.

[206] Mourad Bouzit, Grigore Burdea, George Popescu, and Rares Boian. The rutgers master ii-new design force-feedback glove. *IEEE/ASME Transactions on mechatronics*, 7(2):256–263, 2002.

[207] Kevin Huang, Ellen Yi-Luen Do, and Thad Starner. Pianotouch: A wearable haptic piano instruction system for passive learning of piano skills. In *2008 12th IEEE international symposium on wearable computers*, pages 41–44. IEEE, 2008.

[208] Evren Samur. *Performance Metrics for Haptic Interfaces*. Springer, 2012.

[209] Kourosh Zareinia, Yaser Maddahi, Canaan Ng, Nariman Sepehri, and Garnette R. Sutherland. Performance evaluation of haptic hand-controllers in a robot-assisted surgical system. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 11(4):486–501, 2015.

[210] Hamidreza Hoshyarmanesh, Kourosh Zareinia, Sanju Lama, Benjamin Durante, and Garnette R. Sutherland. Evaluation of haptic devices and end-users: Novel performance metrics in telerobotic microsurgery. *The International Journal of Medical Robotics and Computer Assisted Surgery*, 16(4):e2101, 2020.

[211] Hamidreza Hoshyarmanesh, Kourosh Zareinia, Sanju Lama, and Garnette R. Sutherland. Structural design of a microsurgery-specific haptic device: neuroarmplushd prototype. *Mechatronics*, 73:102481, 2021.

[212] T Sugiyama, S Lama, LS Gan, Y Maddahi, K Zareinia, and GR. Sutherland. Forces of tool-tissue interaction to assess surgical skill level. *JAMA Surg.*, 153(3):234–242, 2018.