Chapter 2
State of the Art

Abstract Haptic interfaces generate the sense of touch in the form of force or tactile feedback and allow us to touch and manipulate objects either within a virtual environment or in a real world through a slave of a teleoperated system, such as for surgical robotics. There has been considerable amount of research on the haptic technology, which brought it into computer games, surgical simulators, mobile phones etc. A closer investigation of these devices and studies on their performance evaluation shows that type of evaluations, aim of methods and performance metrics vary considerably depending on the device. We have, therefore, reviewed the evaluation methods in the literature that have been applied to haptic devices. In this chapter, first, commercially available haptic interfaces and their application areas are reviewed. Then, haptic interface evaluation studies in the literature are discussed and categorized into two groups: physical and psychophysical evaluation studies.

2.1 Haptic Interfaces

Haptic technology deals with the synthesis of touch and force (*haptics*, in general) to enable us to interact with virtual environments through haptic interfaces. In short, haptic interfaces generate the sense of virtual touch in the form of force feedback (for receptors in the muscles and joints) and tactile feedback (for sensors located in the skin). Since the early 1990s, there has been considerable amount of research on the haptic technology which brought it into computer games, surgical simulators, mobile phones etc. The following section reviews the state-of-the-art haptic interfaces.

2.1.1 Force Feedback Devices

2.1.1.1 General Purpose Interfaces

Perhaps the most widely used haptic interface is the PHANTOM® developed by Massie and Salisbury [52] and now commercialized by the Sensable Technologies,

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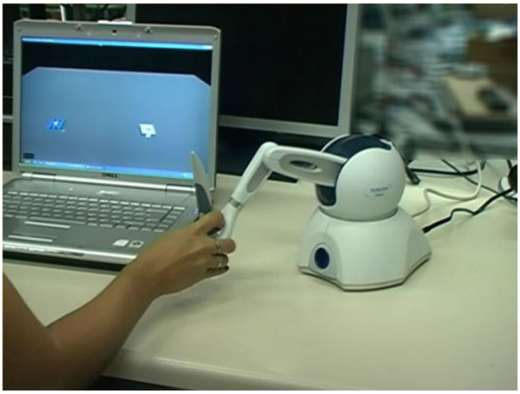


Fig. 2.1 PHANTOM Omni® from Sensable Technologies, Inc.®

Fig. 2.2 The omega.3 haptic device from Force Dimension. This 3-DOF desktop interface with its embedded real-time controller offers a universal interface for standard haptic applications. Photo courtesy of Force Dimension

Inc.® [74]. Different versions are available, ranging from a low cost desktop application (PHANTOM Omni®, 0.055 mm position resolution, peak force 3.3 N) to a high-end research tool (PHANTOM Premium 1.5 High Force/6-DOF, 0.007 mm position resolution, 37.5 N peak force). As shown in Fig. 2.1, the stylus of PHANTOM Omni enables position and orientation input in 6-DOF while force feedback is only in 3-DOF. Recently, a new handle design for the 6-DOF family of haptic devices permits attaching interchangeable new end effectors providing pinch functionality.

The omega.x, delta.x and sigma.x haptic devices from Force Dimension [25] are of the high performance interfaces. For example, the omega.3 is a 3-DOF desktop interface allowing 12.0 N maximum continuous force feedback with a position resolution of 0.01 mm. Its parallel kinematics (see Fig. 2.2) design enables the omega.3 base to accommodate various interchangeable end-effectors to upgrade to multi-DOF versions. On the other hand, delta.6 is more suitable for various engineering applications and experimentations with its higher workspace and force feedback capability in translational and rotational DOFs (see Fig. 2.3). Due to it is parallel delta structure, it can generate high continuous forces and torques up to 20 N and 0.150 Nm. Finally, the recently released sigma.7 introduces seven active DOFs including grasping force feedback up to $\pm$ 8 N. This high-end haptic device as shown

Fig. 2.3 The delta.6 haptic device from Force Dimension. With its large workspace and active wrist end effector, the delta.6 is suitable for virtual reality based research and engineering. Photo courtesy of Force Dimension

in Fig. 2.4, which has a maximum continuous force and torque of 20 N and 0.4 Nm respectively, is mainly used in the aerospace and medical fields demanding safety-critical applications. The Novint Falcon® (Novint Technologies, Inc.) is a low-cost version of the omega.3 targeting gaming industry, with a peak force around 10 N.

The HapticMaster [86] is the only admittance controlled haptic interface on the market (commercialized by MOOG, Inc. [57]). The admittance control enables it to achieve high force output (max continuous and peak force of 100 and 250 N) and render high impedance. Its large workspace and high impedance characteristics make this device an ideal candidate for the rehabilitation research.

Haption SA provides a wide range of haptic interfaces called Virtuose™ [34]. For example, the Virtuose 6D Desktop used for gaming applications has a maximum continuous force of 3 N, on the other hand, larger version of this device, MAT 6D,

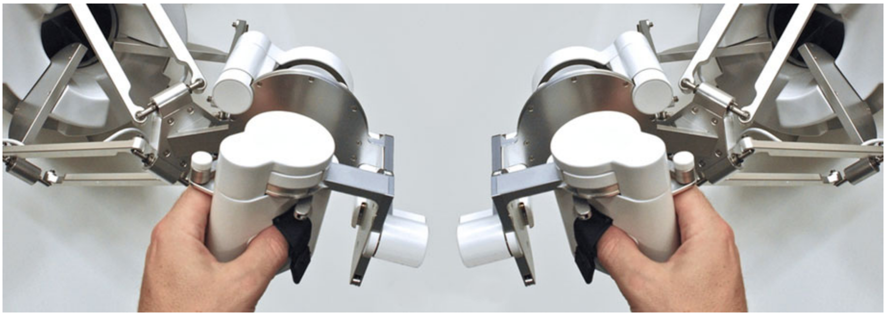


Fig. 2.4 The sigma.7 haptic device from Force Dimension. Being the most advanced haptic interface developed by Force Dimension, it introduces 7 active DOFs, including grasping capability. Photo courtesy of Force Dimension

Fig. 2.5 The 6-DOF VIRTUOSE 6D35-45 from Haption SA. Its large workspace corresponding to the movements of a human arm and 6-DOF force feedback, make it especially suited for one to one virtual object manipulation. Photo courtesy of Haption SA

can generate a maximum of 30 N continuous force and used for teleoperation. Figure 2.5 shows a Virtuose 6D35-45 device which has a workspace corresponding to the movements of a human arm.

The Freedom 7S is a serial force feedback device designed by Hayward et al. [38] and later commercialized by MPB Technologies Inc. [59]. The device is especially designed for medical simulation. Although the maximum continuous force is not high (0.6 N), it has a position resolution of 0.002 mm which makes it suitable for precise applications.

For those looking for a high fidelity desktop device, Quanser Inc. provides two haptic interfaces [66]. First one is the 5 DOF Haptic Wand which is originally designed by the group of Prof. Tim Salcudean at the University of British Columbia, Canada [77]. The haptic interface allows for three translations and two rotations (roll and pitch) by using a dual-pantograph arrangement (see Fig. 2.6). Second haptic interface developed by Quanser Inc. is the 6 DOF High Definition Haptic Device (HD^2) shown in Fig. 2.7. Compared to the Haptic Wand, it has not only one additional DOF but also higher force capability (maximum continuous force and torque of 11 N and 0.950 Nm respectively) and a larger workspace.

Maglev 200™ from Butterfly Haptics, LLC [12] is the only commercially available magnetic levitation haptic interface (see Figs. 2.8 and 2.9). The haptic device employs the principles of Lorentz levitation which eliminates the drawbacks of systems using mechanical elements such as friction, backlash, link bending, and motor cogging. This gives Maglev 200™ superior performance characteristics such as zero backdrive friction, high force bandwidth (2 kHz) and high position resolution (0.002 mm) and high stiffness (50 N/mm). On the other hand, its relatively small workspace (24 mm diameter sphere) limits its application areas. The first generation magnetic levitation haptic device was developed by Prof. Ralph Hollis and his student Peter Berkelman at Carnegie Mellon [8].

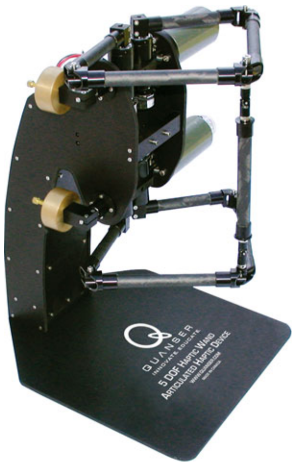


Fig. 2.6 The 5 DOF Haptic Wand, developed by Quanser Inc. and Prof. Tim Salcudean of the University of British Columbia, Canada, is an open architecture solution designed to help research or teach haptics. Photo courtesy of Quanser Inc.

The specifications of the reviewed commercially available force feedback devices are summarized in Table 2.1. As shown in this table, not all the specifications are provided by the manufacturers. Although some specifications such as workspace and continuous force are common, important information on force resolution, transparency and frequency response characteristics is rarely provided.

2.1.1.2 Surgery Simulators

The positive impact of haptic feedback in virtual reality based surgery simulators has been recently proven by clinical trials [3, 5]. This is the reason why haptic interfaces

Fig. 2.7 The 6 DOF High Definition Haptic Device (HD^2), developed by Quanser Inc., is a high fidelity force-feedback platform for advanced research in haptics and robotics. Photo courtesy of Quanser Inc.

Fig. 2.8 Maglev 200™ Magnetic Levitation Haptic Interface is the first commercial haptic device to employ the principles of Lorentz levitation. The handle can be freely moved in 6 DOF with zero friction. Photo courtesy of Butterfly Haptics, LLC

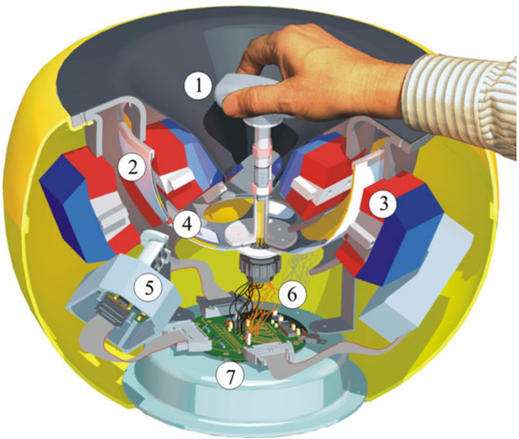


Fig. 2.9 Maglev 200™ cut away picture: (**1**) Handle (or manipulandum), (**2**) Hemispherical "flotor" shell containing 6 spherical coils, (**3**) One of 6 permanent magnet assemblies, (**4**) One of 3 light emitting diodes, (**5**) One of three optical sensor assemblies, (**6**) Flexible wiring for power and signals, (**7**) Interface to controller. Photo courtesy of Butterfly Haptics, LLC

are very successful in this domain. In this section, the companies providing surgery simulation systems with force feedback are discussed.

Mentice [55] uses the Xitact™ IHP in their laparoscopy simulator (Mentice MIST™). The Xitact IHP is a 4-DOF force feedback device which was originally developed by Dr. Vollenweider at Ecole Polytechnique Fédérale de Lausanne [89].

Table 2.1 Specifications provided by the manufacturers of the commercially available force feedback devices

	Phantom Omni [74]	omega.3 [25]	Novint Falcon [62]	Haptic Master [86]	Virtuose [34]	Freedom 7S [59]	HD^2 [66]	Xitact IHP [55]	Maglev 200 [12]
Structure	Serial	Parallel	Parallel	Serial	Serial	Serial	Parallel	Hybrid	n/a
Workspace (10^{-3} m^3)	1.3	2.2	1.1	80.0	91.0	12.0	70.0	1.9	0.01
DOF	6 // 3	3	3	3	6	7	6 // 5	4	6
Position Res. (μm)	55.0	10.0	60.0	4.0	6.0	2.0	51.0	57.0	2.0
Continuous Force (N)	0.9	12.0	9.0	100.0	10.0	0.6	10.8	20.0	n/a
Peak Force (N)	3.3	n/a	n/a	250.0	35.0	2.5	19.7	30.0	40.0
Stiffness (N/mm)	2.0	14.5	n/a	50.0	n/a	2.0	3.0	n/a	50.0
Stiction (N)	0.26	n/a	n/a	n/a	n/a	0.04	0.35	n/a	0.0
Force Resolution (N)	n/a	n/a	n/a	0.01	n/a	n/a	n/a	n/a	0.02
Force Bandwidth (Hz)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	2000

Fig. 2.10 VirtaMed HystSim system employing the Xitact™ IHP as the force feedback interface. Photo courtesy of VirtaMed AG

In addition, Mentice has an endovascular simulator called VIST™ that enables force feedback.

Virtamed [88] is a Swiss start-up company producing HystSim system originally developed by Harders et al. [36]. It enables training of diagnostic and therapeutic hysteroscopy using an original resectoscope and provides objective performance feedback. The prototype of the HystSim used to work with a haptic interface developed at Ecole Polytechnique Fédérale de Lausanne [76]. Currently, it uses the Xitact™ IHP as a force feedback device (see Fig. 2.10).

CAE Healthcare [13] has three simulators that provide force feedback: the LaparoscopyVR, the EndoscopyVR and CathLabVR. The LaparoscopyVR is designed for teaching minimally invasive laparoscopic surgery and force feedback is provided by a 3-DOF device. The EndoscopyVR (formerly AccuTouch System® of Immersion Corp.) is a simulator for teaching and assessing motor skills for gastrointestinal and bronchial assessment. It provides 1-DOF force feedback during insertion and removal of the endoscope. Finally, CAE Healthcare's CathLabVR simulates vascular procedures with force feedback.

Surgical Science [78] has a laparoscopy simulator (LapSim) which is also compatible with the Xitact™ IHP. In addition, together with Ecole Polytechnique Fédérale de Lausanne (EPFL) and Commonwealth Scientific and Industrial Research Organisation (CSIRO), they are developing an endoscopy simulator which includes a 2-DOF force feedback device [70] (see Fig. 2.11).

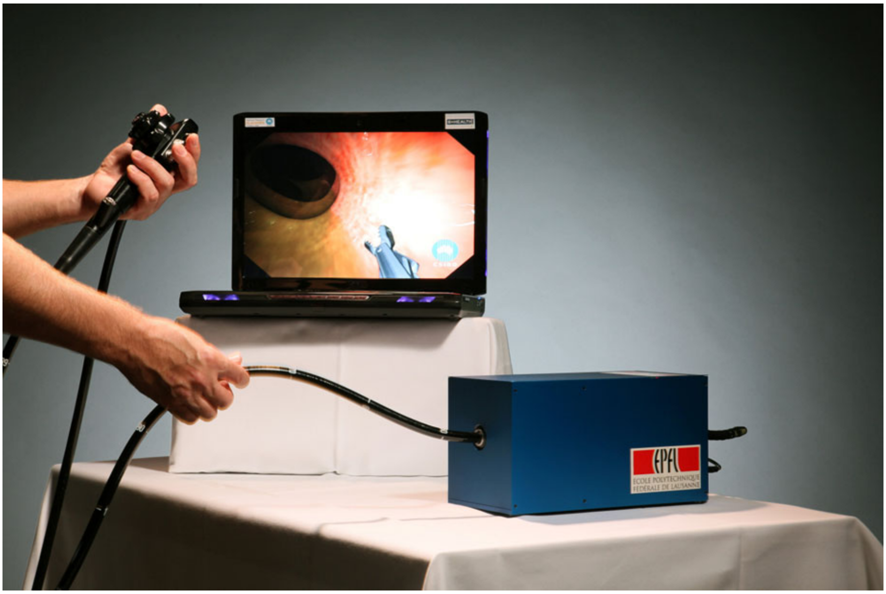


Fig. 2.11 The haptic interface developed at EPFL [70] integrated with the software simulation for colonoscopy (MILX™ GastroSim) developed at CSIRO [19, 39]. The simulator is currently being commercialized by Surgical Science Sweden AB

Simbionix USA Corporation [75] recently introduced the GI-BRONCH Mentor™ a combined platform for GI endoscopy and flexible bronchoscopy. This simulator provides higher force feedback by a pneumatic balloon breaking system, yet the translational and rotational force feedback are not decoupled. Simbionix also offers a laparoscopy simulator (LAP Mentor™) with force feedback.

Mimic Technologies [56] has developed a training simulator (the dV-Trainer™) designed for training of surgeons learning to use da Vinci® Surgical Robotic System from Intuitive Surgical®, Inc. The haptic interface is a novel cable driven system [9].

2.1.1.3 Surgical Robotics

Robotic surgery has been a domain of intense research activity in recent years. Despite the certain benefits such as providing high-definition visualization system and enhanced dexterity, the use of a teleoperated robotic system removes the direct contact of hands with tissues and thus, diminishes the sense of touch. All information about the patient is given to surgeons only through the visual sense. This imposes surgeons to exclusively rely on visual cues, compromising patient safety and telepresence. From the surgeons' perspective the force feedback plays a crucial role for patient safety and intuitiveness [71]. However, up to now, the potential of haptic feedback in robotic surgery has not yet been fully exploited and thus, this application still represents a fascinating research field.

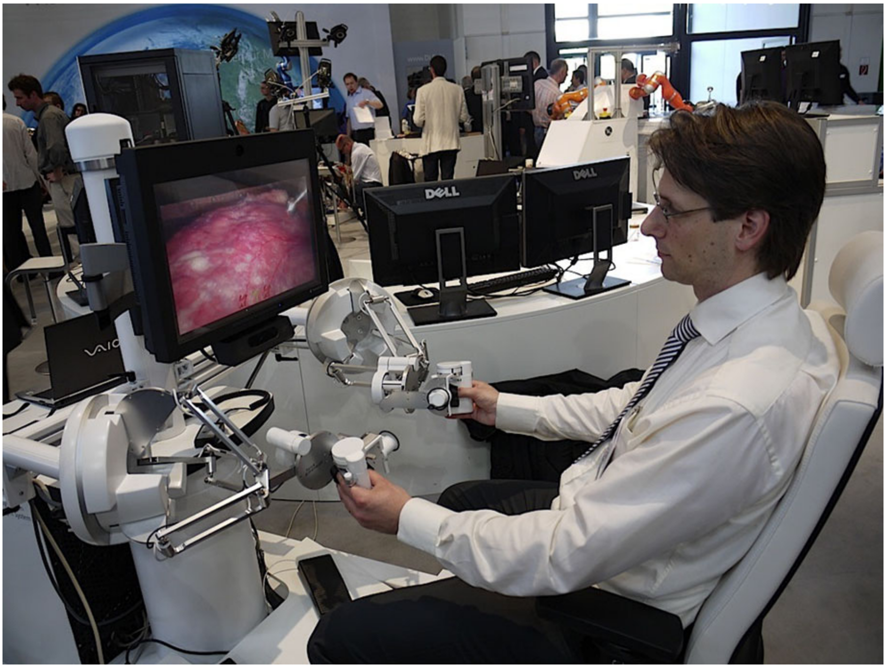
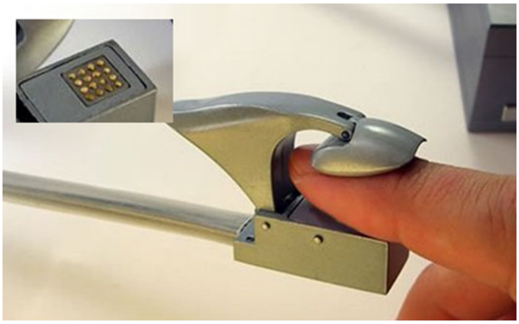


Fig. 2.12 DLR's MiroSurge haptic console consists of two sigma.7 haptic device from Force Dimension. Photo courtesy of Force Dimension

Intuitive Surgical's da Vinci® Surgical System [43] is the leading surgical robot which is used in several operations such as urology, gynecology and general surgery. This system provides 3D steroscopic vision and high dexterity to control the surgical instruments at the tip of the robot. However, force feedback resulting from interaction between the instruments and tissues is neglected and surgeons using this system rely on only visual cues [29]. Since it has been shown that force feedback enhances performance in robotic surgery [45, 72, 73, 90], there have been several efforts to restore the sense of touch when using the da Vinci system. For example, the VerroTouch [54] measures the impact caused by tool contacts inside patients and reproduces them at the level of the master handle. This feedback allows the surgeon to feel important tactile events such as rough surfaces as well as the beginning and the end of contact during manipulations. King et al. [45] developed a tactile feedback system to translate force distribution on the da Vinci surgical instruments to the fingers. In parallel to direct feedback, sensory substitution with imaging techniques is also proposed for restoring haptic feedback [47]. Nevertheless, this extra information should always be introduced carefully to avoid mental (or visual) overload. Despite these efforts to overcome the lack of haptic feedback in the da Vinci system, the proposed methods are still far from being perfect and not available in the commercial version.

Fig. 2.13 Aphee-4x pin-based tactile interface from Aesthesis. Photo courtesy of Aesthesis



The only commercially available tele-operated surgical robotic system with haptic feedback is the Sensei™ X Robotic Catheter System from Hansen Medical, Inc. [33]. This robotic catheter system uses the 3-DOF omega.medical haptic device from Force Dimension to control the tip of the catheter. Force feedback information based on preoperative data is provided to the surgeon in real time, while maintaining patient safety.

Force Dimension has recently developed the sigma.7 haptic device [25] which is dedicated for medical applications. MiroSurge surgical robot from German Aerospace Center (DLR) [30, 82] features two sigma.7 haptic devices which have force feedback in 7 degrees of freedom including grasping (see Fig. 2.12). However, the MiroSurge is not yet commercially available.

2.1.2 Tactile Interfaces

Contrary to vast number of force feedback devices on the market, there are not many commercially available tactile interfaces. Until couple of years ago, pin-based tactile interfaces were quite common. One example to this kind of tactile devices is the Aphee-4x from Aesthesis [2]. This interface consists of an array of 16 fingertip pins arranged in an area of 7 mm^2 and can reproduce surface profiles of virtual objects on the fingertip as shown in Fig. 2.13.

The tactile technology has recently found his common application in mobile phones and gaming interfaces as simple vibrating buzzes. Nowadays, almost all mobile phones have a vibrating mode. Nintendo Wii [61] and Logitech Driving Force™ GT [51] are two examples of tactile interfaces used in computer games for better realism and immersion.

Now tactile technology in touch screens and mobile phones is going beyond the primitive haptics and presenting the boundaries or surface properties of an object on screen as you move your finger over it. TouchSense® tactile technology from Immersion Corp. [42] is claimed to provide "HD haptics" using piezo actuators. This technology is already integrated in Immersion's touch screens and some mobile phones such as Synaptics Fuse [79]. It is also used in cars to facilitate drivers to select an icon on the control menu.

Fig. 2.14 CyberGrasp system is a wearable force feedback system for fingers and hand. Photo courtesy of CyberGlove Systems LLC

2.1.3 Other Applications

Apart from the haptic devices mentioned above, there are also other application areas worth mentioning. Introduction of robotic systems into the area of stroke rehabilitation has improved the therapy outcome. For example, Hocoma AG has several rehabilitation robotic systems which utilize force feedback for locomotion therapy (Lokomat®) and functional therapy of the upper extremities (Armeo®) [40].

In addition to the grounded desktop force feedback devices mentioned earlier, force feedback gloves are also available for gaming and rehabilitation purposes. CyberTouch, CyberForce and CyberGrasp are three different wearable systems from CyberGlove Systems LLC with tactile or force rendering capability for each finger and hand [18]. The CyberGrasp device shown in Fig. 2.14 is a lightweight, force-reflecting exoskeleton that fits over a CyberGlove data glove and adds force feedback to each finger. Grasp forces (up to 12 N per finger) are produced by a network of tendons routed to the fingertips via the exoskeleton.

2.2 Evaluation Studies

A closer investigation of studies on the evaluation of haptic rendering shows that type of evaluations, aim of methods and performance metrics vary considerably in these studies. We have therefore categorized the evaluation methods in the literature that have been applied to haptic interactions including VE, control, device as well as the human operator (see Fig. 2.15). Some of these methods employ only algorithm validation and comparison based on rendering realism [50, 67], whereas some others studied control design and evaluation for haptic interfaces [10, 17, 31, 48].

2.2.1 Physical Evaluation Studies

The discussion about experimental performance evaluation for haptic interfaces goes back to 80s when force-reflecting hand controllers (today's haptic interfaces)

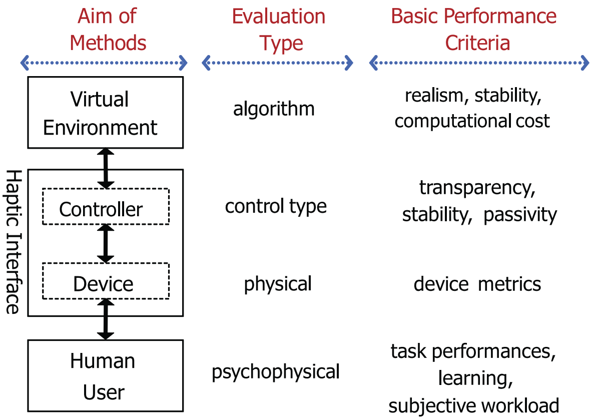


Fig. 2.15 Classification of haptic rendering evaluation techniques and their corresponding basic performance criteria

were used in teleoperation. The design requirements for teleoperation were described by Brooks [11] and used by many researchers. Later, McAffee and Fiorini [53] identified the key performance characteristics of the hand controllers and quantitatively compared existing devices. Hollerbach et al. [41] made a comparative analysis of actuator technologies for robotics. One of the detailed studies to measure force output performance of a robot was carried out by Eppinger [22]. He modeled the robot dynamic performance and conducted experiments to extract the effect of different components of the robotic system. Hayward and Astley [37] theoretically defined performance measures directed towards isotonic (i.e. impedance type) devices. More or less at the same time, these measures were formalized for coupled micro-macro actuators by Morrell and Salisbury [58]. In addition, practical ways to measure them were experimentally demonstrated on a haptic interface by Ellis et al. [21]. Several projects [1, 7, 23, 27, 65, 70, 87, 95, 96] evaluated particular haptic devices based on these technical performance metrics (these metrics are studied in detail in Chap. 4). An experimental identification method was described by Frisoli and Bergamasco [26]. Similarly, the dynamics of PHANTOM Premium 1.5A (Sensable Technologies Inc.) were experimentally identified by [14, 80]. Ueberle [84] conducted hardware experiments for the comparative performance evaluation of haptic control schemes using the VISHARD interface [83]. Weir et al. [93] described methods to measure impedance distribution of a haptic device over frequency based on the *Z-width* concept [17]. A method was proposed by Chapuis to calculate the output impedance of a device using the electrical analogy [15].

2.2.2 *Psychophysical Evaluation Studies*

There are many human factor studies to asses the benefits of haptic feedback on sensory-motor control tasks. Peg-in-hole [32, 85], tapping [16, 92], targeting [63], haptic training [4], joint tasks in a shared VE [6] and object recognition [64, 81, 94] tests are the most frequently performed experiments in these studies. Lawrence et al.

[49] performed some psychophysical experiments to ascertain whether human perception of differences in hardness depends more on high frequency or low frequency impedance differences.

In spite of the large number of psychophysical studies, only few of the tests have been used to measure the performance of a haptic interface rather than the haptic feedback itself. Wall and Harwin [92] employed a tapping test in conjunction with Fitts' law [24] in order to establish a measure of human performance in a simple target selection task. They showed that the providing force feedback significantly reduced subjects' movement times. In another study [91], they measured the performance of their high bandwidth device in a perceptual context of roughness [94] in order to fully evaluate its contribution to the haptic system. They demonstrated that different haptic interfaces have different performance characteristics in rendering the surface roughness. Harders et al. [35] performed 3D peg-in-hole tests to compare three different haptic devices. Rendering hard virtual walls has been the most mentioned benchmark topic in evaluating the performance of haptic interfaces. Lawrence et al. [49] introduced rate-hardness as a quality metric which is more relevant than mechanical stiffness in perception of hardness. Guerraz et al. [28] suggested to use physical data from a haptic device to evaluate haptic user interfaces. Kappers et al. [44] performed haptic identification experiments using quadric surfaces and showed that both shape index, a quantity describing the shape, and curvedness had significant effect on haptic shape identification. Based on this research, Kirkpatrick and Douglas [46] used shape recognition as an evaluation method for a complete haptic system. Their protocol can be used as a benchmark task to evaluate new haptic interface designs but it does not comprise all haptic interactions. Moreover, Tan [81] applied the absolute identification paradigm to sphere size identification for human performance estimations. Results were expressed in bits of information transfer and showed that humans could correctly identify at most 3 to 4 sphere sizes (corresponding to 2 bits) ranging from 10 to 80 mm in radius using the PHANTOM. This conclusion is also consistent with the results of manual length identification with physical objects [20], thus 2 bits of information transfer (IT) can be used as the threshold of identification performance of human for device evaluation. Murray et al. [60] used this information transfer concept to evaluate their wearable vibrotactile glove. Salisbury et al. [68, 69] used detection psychophysical experiments to measure device performance using vibrotactile stimuli. Their results indicated that none of the haptic devices tested were able to render perceptually distortion-free vibrations at detection threshold levels.

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