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Toward Whole-hand Kinesthetic Feedback: A Survey of Force Feedback Gloves

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Abstract—Force feedback gloves have found many applications in fields such as teleoperation and virtual reality. In order to enhance the immersive feeling of interaction with remote or virtual environments, glove-like haptic devices are used, which enable users to touch and manipulate virtual objects in a more intuitive and direct way via the dexterous manipulation and sensitive perception capabilities of human hands. In this survey, we aim to identify the gaps between existing force feedback gloves and the desired ones that can provide robust and realistic sensation of the interaction with diverse virtual environments. By examining existing force feedback gloves, the pros and cons of existing design solutions to the major sub-systems including sensing, actuation, control, transmission and structure are discussed. Future research topics are put forward with design challenges being elaborated. Innovative design solutions are needed to enable the utility of wearable haptic gloves in the upcoming virtual reality era.

Index Terms—Haptic glove, force feedback, tactile feedback, virtual reality

1 Introduction

FORCE-feedback gloves are valuable in fields such as teleoperation, master-slave manipulation, virtual reality (VR), and rehabilitation. Compared with desktop haptic force feedback devices such as Phantom Desktop, force feedback gloves are able to allow users to touch and manipulate remote or virtual objects in an intuitive and direct way via the dexterous manipulation and sensitive perception capabilities of our hands. A well designed glove could provide force and tactile feedback that realistically simulates touching and manipulating objects at a high update rate, while being light weighted and low cost.

Although a few surveys related to the glove based systems were made before [1] [2], they were for the purposes other than this survey where by examining and comparing the different gloves, we classify existing haptic gloves and consequently present design guidelines for the key components of a force feedback glove, including actuation, sensing, transmission, control and mechanical structure. In this paper, we survey the technologies available, identify the drawbacks of existing designs of the gloves, find the challenges in designing a high-fidelity glove, and then point out the new directions of research in the field.

The sources of this survey include IEEE Xplore, ACM Digital Library, Pubmed, Web of Science, and Google Scholar. To focus on the theme of providing kinesthetic stimuli (i.e. force feedback) to a user's hand, we excluded those references on motion/force sensing gloves without force feedback. Readers may refer to previous survey on these gloves [1]. We also excluded those works of providing solely cutaneous stimuli on fingers. Readers may refer to a recent survey on hand-based and fingertip-based cutaneous feedback devices [2]. Lastly, in this paper, we focused on the hardware technology other than rendering algorithms and software development for haptic gloves.

The remainder of this paper is organized as follows. In Section II, the design challenges of haptic gloves are summarized by analyzing the anatomical characteristics of the hand and the key factors for an ideal haptic feedback glove. In Section III, a summary of existing prototypes and products of haptic gloves is provided from the point of view of potential users. In Section IV, we provide an in-depth analysis of the major sub-systems including sensing, actuation, control, transmission and structure etc, and make comparisons among the technologies used. Future research topics are proposed in Section V, followed by a conclusion in the last section.

2 Design Challenges of Force Feedback Gloves

In this section, we examine the mechanical and biological features of human hands in order to identify the design challenges of a kinesthetic feedback glove and define its functions and specifications.

2.1 Biological features of the human hand

The biological features of the human hand can be analyzed from three aspects: anatomic structure, motor control, and tactile/proprioceptive sensing [3] [4].

Understanding the anatomic structure and the biomechanical characteristics of the hand, especially the fingers, is essential to developing a haptic glove. Including the wrist, the human hand is usually modeled with 21 Degrees of Freedom (DoF) of movement [3]. Each finger

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except the thumb has three bones (distal, middle, and proximal phalanges), and three joints (MCP, PIP, and DIP joints). The thumb has two bones (distal and proximal phalanges) and two joints. Unlike the other four fingers, the metacarpal phalanx of the thumb can be moved around the carpometacarpal (TMC) joint near the wrist, which allows for the complicated movements of the thumb. Each PIP or DIP joint has one DoF for flexion/extension, while each MCP joint has one DoF for flexion/extension and one more DoF for adduction/abduction.

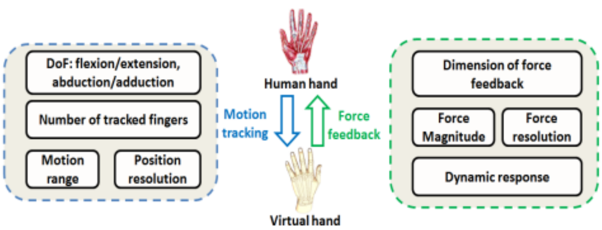
In addition to the aforementioned characteristics of the fingers, kinematics behavior of the human hand needs to be considered for designing force feedback gloves. The movement range [3] [5] and accuracy [3] [4] [6] of diverse finger joints dictate quantified specifications for tracking systems of force feedback gloves.

From the perspective of force feedback, understanding the characteristics of the mechanoreceptors in the skin, muscles and joints is necessary to determine the required force control accuracy and bandwidth of a force feedback glove. Major features of mechanoreceptors, such as high perception resolution [3], pose great challenges in simulating realistic force and tactile feedback through a glove. For example, the force control error of a glove should be smaller than the discrimination threshold for force perception, which averages 7-10% over a force range of 0.5-200N [3]. In order to develop high-fidelity force feedback gloves, it is necessary to carefully examine the detection and discrimination threshold of proprioceptive receptors including muscle spindles and Golgi tendon organs, along with that of joint receptors in capsules and ligaments of joints.

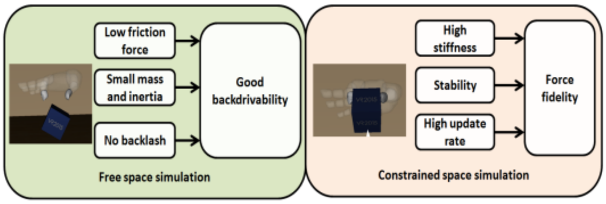
2.2 Specifications and Challenges of High-Fidelity Force Feedback Gloves

Similar to desktop force feedback devices [9], two principles were used for controlling the gloves, i.e., impedance and admittance control. The former relies on sensing the fingers motion and applying feedback force to the fingers. The latter is opposite. In this section, we use the impedance principle to explain the design specifications. The comparison between the two control principles is elaborated in Section 4.5.

As shown in Fig. 1, an impedance display glove has two basic functions: (1) motion tracking: sensing of the motion of multiple fingers, and (2) force reflection: apply resistant force on fingers. Each function can be quantified by some relevant performance metrics. It should be noted that for admittance type gloves, force sensing is needed to infer the users' behaviors.



a) Two major functions and corresponding specifications.



b) Integrated performance metrics (Pictures adapted from [10].)

Fig. 1 Performance metrics of an impedance display glove.

As shown in Fig. 1-a), motion tracking is necessary to detect users' manipulation gestures and to drive the motion of a hand avatar in virtual environments. Following specifications are widely used to quantify the performance of motion tracking, including motion range, sensing accuracy, and update rate. High DoF and large motion range are required for simulating dexterous manipulation and variable grasping configuration. Furthermore, high accuracy and update rate are required for simulating fine manipulation and rigid object grasping. Usually, the update rate of 1 kHz is required to achieve stable force feedback [11] [12] [13] [14].

For force reflection, following specifications are widely used, including dimension, range of applicable force, resolution and dynamic response of feedback forces. For simulating contact forces during dexterous manipulation and power grasping of virtual objects, three dimensional force/torque and sufficient range of force magnitude are required. For simulating subtle changes of contact forces between fingers and rigid objects, high force resolution and dynamic response are required. In some tasks that require accurate force feedback such as palpating a virtual tumor in surgical simulation, the error of feedback force should be smaller than human's discrimination threshold of force magnitude, and thus the user can infer the tumor's stiffness via the relationship between the resistance force and the hand movement.

Inspired by the three criteria proposed by Salisbury *et al.* [15], as shown in Fig. 1-b), we summarize the following integrated performance metrics for a force feedback glove:

1. Backdrivability: based on the criterion of *free space must be free* [15], the metrics of free space simulation could be the backdrivability, i.e. the friction and inertial force should be less than human's detection threshold on force magnitude.
2. Achievable stiffness: based on the criterion of *solid objects must be felt stiff* [15], one important metrics of constrained space simulation could be the maximum achievable stiffness of the virtual object, i.e. the equivalent stiffness on the fingertip should be sufficiently large to simulate stiff object.

In addition to the above two performance metrics, other important issues of a high performance force-feedback glove are wearability, the method of mounting the glove to the human hand, the way of transmitting forces and torques to fingers, and the adaptability to different human hands.

The level of wearability of haptic interfaces can be defined by their form factor, weight, shape, area of interest, and ergonomics [2]. As summarized in [2], in order to

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increase the wearability, one approach is to move the base of the device closer to the application point of the stimulus. However, when the base and the end-effector are placed very close to each other (e.g., the base is on the nail and the end-effector is on the finger pulp), the device can only provide tactile feedback and all the kinesthetic effect of the interaction is lost.

Furthermore, it is desirable that a force feedback glove is comfortable to wear and easy to put on and off. In order to avoid users' fatigue, the glove should be as light-weighted as possible, including its battery and controller.

Last but not the least, a force-feedback glove should be safe. As a wearable device, it should never injure the user even in the occurrence of system failures.

It should be noted that, in practice, quantified requirements of force feedback glove may depend on a specific task. For example, lightweight and low cost are desirable for a force feedback glove for gaming, while a force feedback glove for master-slave operation of a surgical robot may need to provide accurate 3D force and torques at the five fingertips to ensure the quality of the surgical operation.

In some applications, not all the requirements are necessary due to the fact that in many tasks the hand can grasp objects mainly by flexion/extension motion without using abduction/adduction motion. Also, for some grasping postures, the minimum number of fingers required to control an object is usually three rather than five [16]. These facts reduce the challenges of designing a force feedback glove to certain extent.

3 Summary of Existing Kinesthetic Gloves

This section summarizes the existing research prototypes and commercially available kinesthetic gloves, from the user perspective.

3.1 Categorization of Existing Gloves

Fig. 2 illustrates a few examples of force feedback gloves, including both commercial products and research prototypes. One of the earliest kinesthetic gloves was developed by Iwata in 1992 [17]. Thereafter, many gloves have been developed using different actuation principles or different transmission mechanisms.

Force-feedback gloves are complex, and in this survey we classify them by the location of the actuation, or the base frame of the gloves. There are two reasons of using this classification method.

First, this method is intuitive and results in only four sub-categories, which are ground-based, dorsal-based, palm-based, and digit-based gloves.

Second, the location of the actuation strongly affects the magnitude and accuracy of the feedback force, as well as the weight and size of the glove. High force requires large motors or high transmission ratios, which leads to heavy weight or low force accuracy due to large friction in transmission. To make a trade-off between the above key parameters, diverse solutions have been proposed, in which different locations of actuation and types of transmission were explored.

3.1.1 Ground-based systems

Ground-based systems are those with the base being fixed on the ground or a desk. An example is HIRO III (Fig. 2) [18]. It uses a 6-DoF robotic arm and a five-fingered haptic hand (with each finger having 3 DoFs) to provide force feedback at the five fingertips. The robotic hand is connected to the user's hand through finger holders and passive spherical magnetic joints. HIRO III has a larger force output and a wide force direction, and can simulate weight sensations of virtual objects. One of its disadvantages is that the workspace is relatively small compared to the body-based systems because of the limited workspace of the grounded robot arm. Another disadvantage is that the gestures are limited because of the interference between the user's fingers and the robot hand.

Liu *et al.* developed a multi-finger haptic interface named SPIDAR-MF (Space Interface Device for Artificial Reality Multi-Finger) [19] [20], which uses 20 cables to transmit the torque from grounded motors to the five fingertip caps. Thus it can display a 3 DoF spatial force on each fingertip of a human hand through 4 cables. The device can also simulate weight sensations of virtual objects during grasping manipulation.

This type of ground-based systems is able to simulate both force feedback at the fingertips and can simulate external forces, such as weight sensation and inertia of a virtual object, collision with another virtual object, etc, but they are bulky and less suitable for wearable and mobile scenarios.

3.1.2 Dorsal-based systems

The second type of gloves is wearable exoskeleton systems grounded to the back of the hand. A string-based glove was developed at the University of Tsukuba [17]. With the motors placed on the back of the hand, the glove can provide up to 7-N feedback force to the index finger and the thumb. It weighed 0.25 kg. Another string-based glove was the Laboratoire de Robotique de Paris (LRP) hand master [21]. The glove provided up to 14N feedback forces to all fingers and transmitted forces from 14 motors placed in a remote box via microcables, pulleys, and flexible links. In 1997, the Sensor Glove II was developed at the University of Tokyo [22]. The glove had 20 DOFs, while each joint was driven by motors and wire transmission was used to reduce the weight.

The CyberGrasp, introduced in 1998, is one of the most representative example of commercial force feedback gloves [23]. The glove can apply a pushing force up to 12N to each fingertip. The force is transmitted by tendons and exoskeletons mounted on the back of the hand. The device exerts grasp forces roughly perpendicular to the fingertips in the range of motion. The glove has a light weight of 450g. The CyberGrasp requires an additional device, such as the CyberGlove, to provide finger movement sensing [23].

Other dorsal-based force-feedback gloves were developed using different solutions, such as passive spring and clutch [24], wire-driven [25] [26], magnetorheological fluid [27] [28] [29], and micro hydraulic systems [30].

Nakagawara *et al.* developed a multi-fingered master

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hand using the encounter-type force feedback [31], where a compact exoskeleton mechanism called "circuitous joint" was employed, which covers a wide workspace of an operator's finger. The encounter-type force feedback was realized using a photo reflector and a force sensor. By measuring the distance between the tip of the master finger and that of the operator, the robotic fingers are controlled to contact the operator's finger only when the slave hand touches an object.

Allotta *et al.* [32] developed a 4-fingers exoskeleton that uses a parallel kinematic chain to provide force feedback for each finger module. The end-effector of the device was placed at the fingertip, while the device was grounded on the back of the hand. The exoskeleton is compact and lightweighted of only 330 g. Stergiopoulos *et al.* [33] developed a 2-finger exoskeleton for virtual reality grasping simulation. The device has 3-DoF at the index finger and 4-DoF at the thumb. Full finger flexion and extension was supported and kinesthetic feedback in pull and push directions were provided. Arata *et al.* [34] presented a lightweight hand exoskeleton of 320 g in weight. By exploiting deformations of a compliant body, the mechanism of the exoskeleton transmits 1-DoF actuated linear motion into three rotational motions of the finger joints.

Sarakoglou et al. presented a 3-digit hand exoskeleton, which applies the feedback force with a single attachment at the fingertip through a 6DoF kinematic chain [47]. The under-actuated mechanism provides a bi-directional feedback force at the fingertips. The kinematic chain allows for unconstrained reach of the fingers and also facilitates a sensor system to achieve high resolution 6DoF tracking of the fingertips.

Compared to ground-based systems, one advantage of the dorsal-based gloves is able to simulate force feedback at the fingertips in wearable and mobile scenarios. However, it is difficult for the dorsal-based gloves to simulate weight sensations of virtual objects. Although weight sensations can be elicited by cutaneous feedback device using tactile illusion effect [2], adding kinesthetic stimuli can provide more compelling weight sensations.

Another issue is that most dorsal-based gloves typically use only one wire/tendon to transmit force for each finger. When the glove generates force by using only one wire, the force applied to the fingertip is exerted in the direction that the wire pulls, which leads to a one-dimensional force exerted on fingertip. In comparison, the ground-based systems such as HIRO III can present three-dimensional forces to users' fingertip. To solve this issue, novel transmission mechanism needs to be explored. For example, Koyama *et al.* [24] and Frisoli *et al.* [35] developed exoskeleton-type haptic interfaces that can present three-directional force at human fingertips. They used a serial link mechanism to present a three-dimensional force at two or three of the user's fingertips. Iqbal *et al.* [36] presented a hand exoskeleton that can provide 4 DoF per finger (1 active) and up to 8 N at the fingertip.

3.1.3 Palm-based systems

In order to make the form factor smaller and reduce the weight, other researchers have explored providing force directly between the fingers and the palm to simulate palm opposition type grasping. This type of glove systems is grounded to the users' palm.

The Rutgers Master II—New Design (RMII-ND) uses linear pneumatic pistons distributed in the palm for providing forces between the palm and fingers [37]. Pistons are directly attached to the fingers and provides up to 16 N forces to each fingertip, while the graphite-on-glass pistons significantly reduce the static forces when the glove is powered off. While the working portion of the device is light (about 100g), the workspace is limited as the pistons in the palm limit the user's finger movements. In addition, the compressor adds the weight into the devices. Recently, Zubrycki *et al.* and Simon *et al.* have investigated the use of particle jamming to provide resistance between fingers and the palm [42][49]. The device is composed of tubes and wires running along the finger.

3.1.4 Digit-based systems

The fourth type is the one grounded to the digit. This type of devices provides forces directly between the fingers and the thumb to simulate pad opposition or precision type grips.

Zhang et al. used electroactive polymer actuators to design a glove (DESR) that provides forces between the thumb and forefingers [40]. While the glove is lightweighted, it only allows for a limited range of fingers motion. In order to simulate objects held in pad opposition (precision) type grasps, Choi et al. developed a lightweighted device that renders a force directly between the thumb and three fingers [38]. By using brake-based locking sliders, the system can withstand over 100N force between each finger and the thumb. While this device can allow a large range of motion and provide high resistance forces, it cannot simulate variable stiffness.

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Table 1 Performance comparisons of typical existing kinesthetic gloves (A.M. means Attachment method. N.A. means not available)

Prototype	Performance												
	Motion tracking				Force Feedback			Stiffness	Ergonomics				
	DoF	Motion range	Resolution	Sampling rate	Max. fingertip force	Actuated DoF	Update rate	Stiffness type	Weight	A.M.	Power method	Hand size adjustable	Power consumption
HIRO III [18]	15	Thumb: 705 cm^3, Others:587cm^3	N.A.	1kHz	Over 3.6N	15	8Hz	Variable stiffness	900g	Finger holder	External cable	Yes	N.A.
CyberGrasp [23]	N.A.	Full hand closing	< 1°	112 records/sec	12N	5	1000 Hz control, 40 Hz at fingertip	Variable stiffness	450g	Finger cap	External cables	Yes	N.A.
Rutgers Master II [37]	20	28-44 mm piston stroke	0.45°	435 records/sec	16N	4	300 Hz valve control, 10 Hz at fingertip	Variable stiffness	80g	Finger cap	External cables	Yes	N.A.
Wolverine [38]	18	Virtual sphere with 20-160 mm diameter	N.A.	100Hz	106N	3	N.A.	Constant stiffness	55g	Velcro straps	Battery	Yes	Run on a 350mAh battery for 5hrs
Dexmo [39]	11	N.A.	0.5°	20Hz	N.A.	5	Delay for each FFU is 20–40ms	Variable stiffness	270g	Finger cap	Battery	No	Run for 4 hours with a 800mAh battery
DESR [40]	12	5mm piston stroke	N.A.	N.A.	7.2N	3	N.A.	Variable stiffness	38g	Finger cap	External cables	Yes	N.A.
RML Glove [41]	6	full flexion and extension	0.4°	1.3 kHz	10N	2	30 ms time delay	Variable stiffness	180g	Finger cap	Battery	Yes	Run for 1h with a small capacity battery
Jamming tubes [42]	N.A.	full flexion/ extension	N.A.	N.A.	7N	N.A.	N.A.	N.A.	40g	Glove	N.A.	No	N.A.
FFHG [43]	15	Maximum of 150deg	N.A.	300Hz	10N	5	N.A.	Variable stiffness	310g	Elastic bands	Battery	Yes	Run for 40min with a 9V battery
HEXOSYS [44]	8	N.A.	0.08°	N.A.	45N	2	N.A.	Variable stiffness	400g	Velcro belt	N.A.	No	N.A.

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Fig. 2 Examples of existing force feedback gloves

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3.2 Summary on Major Performance Metrics of Existing Gloves

As we mentioned in Section 2, for simulating high-fidelity haptic interaction tasks, a haptic glove should be safe, able to support free motion of fingers, and present not only three-dimensional force at the contact points but also weight sensations of virtual objects. In addition, it should neither cause an oppressive feeling when attached to the user's hand, nor present its own weight.

From the existing force feedback gloves, we selected several typical gloves for further analysis on their performance. As shown in Table 1, comparisons among typical gloves were made in terms of four categories of performance metrics that are motion tracking, force feedback, stiffness, and ergonomics.

Based on the information in Table 1, we found that the actuated DoFs for most gloves are usually much smaller than their sensing DoF. Except for the HIRO-III, the actuated DoFs of all gloves are equal or less than 5, which means for each finger only one actuator is used to produce force feedback. The main reason for adopting a small number of the actuated DoF is to avoid the heavy weight caused by additional actuators, and thus to achieve a light-weighted structure. However, this solution loses the capability of simulating three dimensional forces on the fingertip.

Among existing force feedback gloves, only a few of them are commercially available, e.g. CyberGrasp and HGlove are two representative examples. Compared to the prosperity of commercial desktop force feedback devices such as Phantom, Omega and Virtuose devices, the lack of available commercial haptic gloves is a bottle neck for studying glove-based haptic interaction, e.g., for developing and evaluating different virtual grasping simulation systems on a uniform platform.

For desktop force feedback devices such as Phantom desktop [50] and Omega.3 [51], detailed performance metrics such as the maximal stiffness in constrained space, and the equivalent resistance force (in terms of friction and inertia forces) in free space is provided. However, for force feedback gloves, very few systems provide quantified performance data. For example, for CyberGrasp, none of the quantified data on backdrivability and the maximal stiffness is available. For RMII-ND glove, the simulated maximal stiffness is not available. The absence of these key performance metrics makes the objective comparison and evaluation hard, and restricts the applications of these gloves in fine manipulation scenarios that need accurate force feedback such as precision grasp and assembly of delicate mechanical parts.

It should be noted that a few gloves do provide a quantified value on the key performance metrics of the maximal stiffness. Wolverine [38] provides the value of maximal stiffness at 162N/mm. Because it is based on passive brake actuation principle, it can only simulate constant stiffness instead of variable stiffness. HIRO III provides the value of maximal stiffness at 5 N/mm. This glove is ground-based and it is hard to be used for mobile applications.

4 State-of-the-Art of Major Components

In this section, the state-of-the-art component technologies used in haptic glove systems are reviewed. For each component, its working principle, performance metrics, and the pros and cons of different design solutions are briefly described and compared.

4.1 Major Components of a Force Feedback Glove

Fig. 3 illustrates a force feedback glove using the impedance control principle, which includes the following components: sensing, actuation, transmission, control and mounting. As illustrated in Fig. 3, the design of these subsystems is not independent; in other words, there are coupling issues between the major performance metrics and different components/sub-systems. For example, impedance range or the achievable maximal stiffness for ensuring the stability of haptic interaction is determined by the performance of the mechanical parts (in terms of friction, backlash and stiffness), the resolution of the sensors, as well as the update rate of the control system.

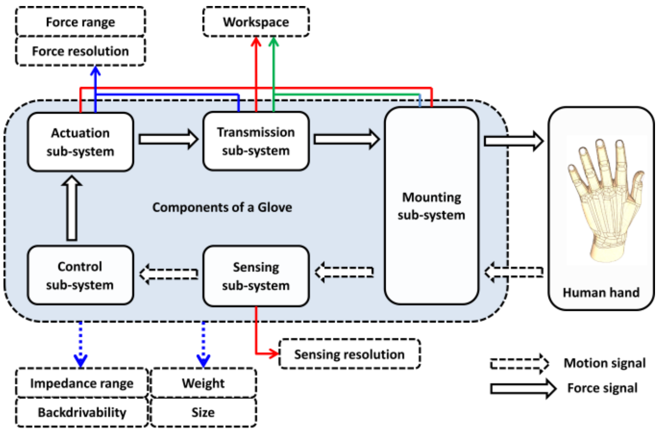

Fig. 3 Major components of a force feedback glove using the impedance control principle

To meet the functional requirements and performance specifications proposed in Section 2.2, there are three challenges for designing a high-fidelity kinesthetic glove:

- The contradiction between the free and the constraint space, i. e., the lowest equivalent inertia/mass perceived by user's hand and the maximal achievable stiffness of virtual contacts. This challenge imposes design constraints for actuation, transmission, and control sub-systems.
- Producing 3D force feedback on the fingertip by transforming the actuating force/torque from the actuator. This challenge relies on designing a transmission sub-system that can allow free motion of the fingertip, enable large stiffness, and avoid bulky size.
- Wearability for hand with different size at a cost as low as possible. This challenge imposes design constraints for actuation, transmission, and mounting sub-systems.

4.2 Sensing

The functions of the sensing system include accurate tracking of whole hand motion in real time, and allow

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sufficient workspace of all the fingertips. In this section, we make a brief summary of the motion sensing and force sensing used in gloves. Readers may refer to previous surveys on sensing gloves for more details on various sensing principles used in gloves [1].

The most common methods used for measuring hand motion include glove-based electro-mechanical sensing devices [1] [53] [54], marker-based [55] [56] [57] or markerless [58] [59] hand motion tracking.

Most gloves were made from plastic or Lycra to allow flexible movement, while a variety of sensors are used to measure the angle of the bend, such as resistive ink sensors, flexible tubes, strain gauges and optical fibers [1]. The gloves are inexpensive, lightweighted, but may not be sufficiently accurate.

Marker-based systems usually adopt surface markers and image sensors (e.g., the Vicon motion systems). These systems offer higher precision and faster measurements than the markerless vision-based hand sensing system. However, this solution is inconvenient since a number of the markers need to adhere to the hands. Furthermore, time-consuming calibration is required to ensure the accuracy of the system.

Markerless visual tracking systems have the potential to provide natural, noncontact methods. However, since the hand contains 21 DoFs, such high dimensional state-space usually requires intensive computation, and thus leads to a low update rate for finger movement sensing.

In addition to motion sensing, force sensing is also useful in haptic gloves using the impedance display principle, as it can be used for closed-loop control of the fingertip force to achieve accurate force feedback. One typical method is to insert a thin force sensing resistor (e.g., FSR, InterLink Electronics Inc.) between the fingertip and the object [61][62]. The advantages of these sensors include low cost, small thickness and flexibility. Thus they can easily fit in a data glove. However, one drawback is that the sensor may impede user’s tactile sensation since the sensor is located between the fingertip and the glove [63]. Furthermore, the nonlinearity, drift, saturation and hysteresis of the FSR prevent them to be used in high precision applications.

Mascaro *et al.* proposed a camera-based method to detect contact forces by analyzing the color change of a fingernail [64] [65] [66]. This method allows the finger to directly contact the object without obstructing finger's natural tactile sensations. Recently, a new method was proposed without putting any sensors between the finger and the object [67]. The main idea is to measure the changing width of the finger that produced by the normal deformation of the fingerpad during a grasping action.

In addition to force sensing at fingertips, torque/current/force sensing at the actuator level can also be used to provide sensing information. The potential limitation is that the force error at the fingertip introduced by the transmission mechanism cannot be compensated using the force sensors located at the actuator level.

4.3 Actuation

For wearable force feedback gloves, the challenges of designing actuation subsystems lie in that they should provide sufficient forces to restrict or stop the motion of the fingers for simulating power grasp, while be small enough to be placed on the hand. As mentioned in Section 2.1, the sensitive perception feature of the human hand imposes a great challenge on the design of actuation systems. The major challenges include how to ensure a sufficient range of output force, high resolution of the feedback force, and a high update rate (i.e. 1 kHz) of the real time force control. At the same time, the actuation system should allow for a good backdrivability of the glove system to simulate free space sensation when the virtual avatar of the hand does not contact other objects in the virtual environment.

The desired design requirements of actuation subsystems had been identified in previous studies. In [68], the authors summarized the design requirements of actuators in a haptic glove. They note that the actuators must have very low friction when they are in the off-state, a sufficiently high force in the on-state to convince a person that he/she is touching a solid object, as well as a low weight. Furthermore, the actuators should be safe since any failure may injure user's fingers.

Most force feedback gloves rely on conventional power producing methods such as electric motors [18] [19] [23] [46], and pneumatics [37] [42] etc. Some gloves adopted actuators based on controllable fluids, such as magnetorheological (MR) fluids [28] [70] [27]. In recent years, soft actuators such as fiber reinforcement strategies [71] and jamming principle [31] have been introduced for haptic gloves. To compare the performance of different actuating solutions, we classified them into two categories: passive and active actuations. According to this classification, Table 2 provides a comparison of typical actuation systems used in various haptic gloves, including actuation type, representative glove systems, performance metrics, pros and cons of each actuation type.

4.3.1 Passive actuation

The passive gloves use a brake, controllable damper or electromagnetic clutch to provide a resistance force [24] [27] [28]. Torques can easily be controlled by the passive devices since they are proportional to the current, or the magnetic field, which excites the coil or the damper. The passive devices never harm the user even in the event of system failure. Therefore, safety is a prominent advantage of these passive actuators. However, they cannot provide any force feedback when the user's hand remains motionless.

One of the typical passive actuation solutions is magnetorheological fluids (MRFs) that contain soft ferromagnetic powder suspended in silicone oil. When a magnetic field is applied across the volume of the fluid, chains of iron particles form in the fluid, thus inducing yield stress. In order to produce motion, a local shear stress larger than this yield stress must be applied to break the chains. The traditional MR devices are large and unsuitable to be used in a glove application. Blake *et al.* developed a force feedback glove that uses compact MR brakes placed on the back of fingers [28]. The glove uses

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four-bar mechanisms to connect six brakes to the digits of three fingers, and does not require any remote box with actuators or sensors. A serpentine flux path is introduced to maximize torque in a compact volume [28]. Although the MRF actuators are inherently safe due to energy dissipation, they are less popular than pneumatic and electric actuators. One reason is because of its slow response (e.g. the time constant of the MR brakes is greater than 60ms [28]).

Another typical passive actuation solution is the use of clutches. A multifingered force feedback glove was designed using clutches and springs [24]. The glove employs a parallelogram linkage attached to the fingertips, and the motion of the linkage is locked or unlocked by the clutches. The applied forces on the user's fingertips are determined by the deflection in the links and the springs at the joints of the finger mechanisms. The maximum applied force is 3 N.

Brakes have also been utilized in haptic gloves. A passive force display glove (PFDG) was developed using electromagnetic On/Off brakes [25]. Four brakes are attached to the back of the hand. Wire–pulley systems are used to transmit braking force to the fingertips and tension on the wires is maintained by a torsion spring. Recently, Choi *et al.* proposed a brake-based locking sliders mechanism for directional braking using an idea of Active Brake Engagement [38]. The system can withstand over 100 N of force between each finger and the thumb, and can support a wide range of motion in a lightweighted, low-cost package; however, it sacrifices active force feedback and the ability to render variable stiffness.

Similarly, Gu *et al.* presented Dexmo, a mechanical exoskeleton that is a lightweighted and safe solution for providing force feedback [39]. A micro servo unit is used to shift stopping blocks linearly to stop the rotation of all joints, and forms a rigid body. The micro servo unit drives two stopping sliders and locks the ratchet wheel firmly in place when the force feedback unit is activated. A disadvantage with Dexmo is that it only provides binary haptic feedback about whether something is present; the softness of the digital object cannot be simulated, which may lower users' immersive experience.

Jamming is a process where a granular material, such as sand or coffee, transitions from a liquid-like state to a solid-like state with a small change in volume [85]. Jamming phenomena can be used to create devices through enclosing granular material in flexible membranes, with fluid (air or oil) being pumped in or removed from between the particles. Using the jamming principle, Zubrycki *et al.* developed a haptic glove for simulating the sensation of grabbing and holding an object [42]. They presented two concepts using either jamming tubes or pads for simulating grasping and exploration tasks. These concepts illustrated a solution of soft, lightweighted, mechanically simple and intrinsically stable mechanism for haptic gloves [42]. Their design is able to resist forces up to 7 N with 5 mm displacement when a micro vacuum pump is used as vacuum source. The force magnitude is smaller but comparable to commercial devices (CyberGrasp can resist a maximal force of 12 N).

4.3.2 Active actuation

The active force feedback gloves can provide not only active motion, but also resistance force or torque.

The most common active actuators are DC servo motors [23] [24]. As the electric motor normally produces torque, a transmission system is needed to transmit the torque into the fingertip force. The other typical actuators are pneumatic actuators, such as those used in Rutgers Master II [37]. Using pneumatic balloon actuators and air jet nozzles, Tanaka *et al.* [72] presented a haptic glove that is able to provide both kinesthetic feedback to four fingers and cutaneous feedback to two finger pads. Other potential choices of active actuators include Shape Memory Alloys [73], electro-active polymer [74] [75] and artificial muscle [76] [77] [78] etc.

The advantage of the active actuation solution is to provide active control and simulate active force/motion output in a high update rate, while its disadvantage is potential risk of injuring the fingers in the event of a system failure. As the actuators are controlled to provide the force feedback, the device may hurt the user's fingers if the control fails. To avoid this failure, most of the active gloves limit the maximum output force to about 10 N.

In recent years, soft robotic technology has been explored for haptic feedback. Soft robots are made with various grades of silicone material and are embedded with pneumatic channels [79]. Actuated motion is achieved by means of pneumatics. The intrinsic soft and pneumatic nature creates lightweight actuators, which provide safe interface for human-machine interaction. Khin *et al.* presented a fabric-based soft tactile actuator and sensor [80]. Consisting of multi-layer composition of paper and fabric, the tactile actuator includes air channel and actuation site. Driven by pneumatic mechanism, the tactile actuator is able to produce sufficient forces to induce haptic perception at the fingertip. The thin, sheet nature of the material creates compact, lightweight actuators, which improves the payload-to-weight ratio. This opens up the possibility of developing soft gloves.

Polygerinos *et al.* developed a 5-fingers soft robotic glove actuated by hydraulic multi-segment soft actuators [71]. The actuators are placed on the dorsal side of the hand, which avoids the potential interferences between the actuators and the fingers and is able to replicate finger and thumb motions for typical grasping movements. The glove provides 1 active DoF for each finger and has a weight of 285g.

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Table 2 Classification of existing actuation systems

	Actuator type	Glove systems	Pros	Cons
Passive actuation principle	MRF	MR glove [28] Smart Mouse [70] , MRAGES [27]	Intrinsically safe, low voltage	Cannot produce active motion, low response, hard to manufacture, heavy and bulky
	Brakes	Wolverine [38], Dexmo [39] , PFDG [81]	Intrinsically safe, simple structure	Cannot produce controllable force, cannot simulate variable stiffness
	Clutches and springs	MFEHD [24]	Intrinsically safe, simple structure	Cannot produce controllable force, cannot simulate variable stiffness
	Pneumatic jamming	Jamming Tubes [42]	Intrinsically safe, simple structure	Loud noise, low update rate of the servo loop
Active actuation principle	DC servo motor	HIRO III [18], SPIDARMF [19], CyberGrasp [23], Hand Exoskeleton [46]	Controllable force, quick response, easy to control, low cost	Need careful tradeoff design between backdrivability and maximal torque by combining a lightweight motor and a gear box, safety risk when motor fails to work
	Hydro pump and valves	WHGUMHS [77]	Provide sufficient force to resist fingers	large volume, distortion of force sensing
	Pneumatic pump and valves	Rutgers Master II [37], Fabric-based soft glove [82]	Generate sufficient force and torque, work at low air pressure	Loud noise; low update rate of the servo loop
	Shape memory alloy	Haptic glove [73]	Small, lightweight	Hard to control the cooling process, high cost
	Artificial muscle	BFFD [78]	Compact construction, natural compliance, flexible trait, safety, portable	Hard to manufacture, high cost
	Dielectric elastomer actuator	DESR [40]	Small, lightweight, force transmission structure is not necessary	Sufficient electrical safety should be provided since the dielectric elastomer actuator is driven by a high voltage

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Table 3 Design solutions of transmission sub-systems in existing force feedback gloves

Type	Representative gloves	Pros	Cons
Linkage	SAFE Glove [5], MR glove [28], Dexmo [39] Multi-finger hand exoskeleton [44]	Simple mechanism, easy to control	Large volume
Cable	SPIDARMF [19], CyberGrasp [23], MRAGES glove [27], Dual-cable Hand [84],	Small volume, light weight, flexible	Extra structure to fix and tension the cable
Direct drive	Rugters Master II [37], Jamming Tubes [42], DESR [40], Wolverine [38], BFFD [78], Force feedback data glove [45]	Simple mechanism, light weight, low friction	Small output force because of using small-sized actuators
Gear	HIRO III [18]	High accuracy	Backlash, heavy weight
Hybrid (Gear + Linkage + Cable)	RML Glove [41]	Flexible design options	Complex structure

4.4 Transmission Mechanism

In addition to the actuator selection/design, transmission design is a key challenge to ensure the performance of a haptic glove.

As the actuator is normally fixed on the palm or the wrist, and the fingertip moves along a complex spatial trajectory with respect to the back of the hand, a mechanism is needed to transmit the torque of the actuator to the end-effectors mounted on the fingertip of the user, as depicted in Fig. 4.

The first challenge is to realize the multidimensional force feedback on a fingertip. Because the contact location and direction between a fingertip and a virtual object is diverse, the resulted fingertip force may have a wide range of magnitude and/or direction. Most existing haptic gloves can only provide one-dimensional force feedback to the fingertips, i.e. the force direction is always perpendicular to the surface of the fingertip [23] [37]. This is not realistic to simulate diverse grasping scenarios that required varied contact force between the fingertip and objects, especially for simulating slippage sensation. Recently, three-DoF force feedback on the fingertip has been investigated [86]. But, it has not been integrated with a multi-fingered glove that supports whole hand manipulation.

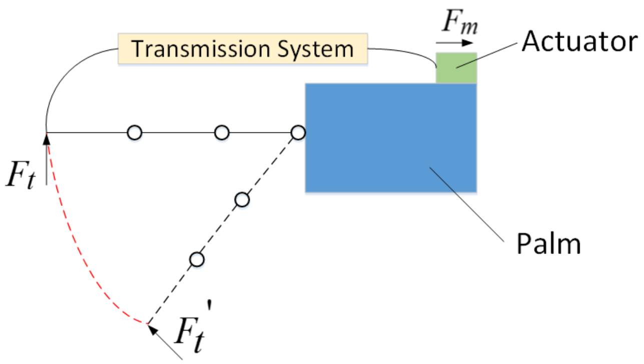

Fig. 4 Force/motion transformation between the axis of the actuator and the normal direction of the fingertip. The dashed line and the solid line represent the initial and the current configuration of the finger. The red curve represents the trajectory of the fingertip between the two configurations, while the fingertip force direction and magnitude might be different between the two configurations.

Another challenge is to consider the seemingly contradicting requirements of the free space simulation and the constrained space simulation. We need to design a mechanism that can transmit the force/torque and motion of the actuator to the fingertips to simulate the constrained space sensation, while still allowing for a free space sensation. As shown in Fig. 4, the trajectory of the fingertip between the two configurations is a curve. A transmission mechanism with a compact and light-weighted structure needs to be designed to produce such a curve. The mechanism should be transparent to the users, which can be decomposed into several engineering design requirements including low friction, small mass and inertia, and no backlash.

In order to fulfill the contradicting requirements of the free and constrained space simulation, various design solutions of the transmission sub-systems in existing haptic gloves have been explored (Table 3). Typical performance metrics of the transmission sub-system are compared in Table 3, which includes transmission ratio, friction, backlash, mechanical stiffness, ease for calibration, manufacturing and assembly complexity.

Fontana *et al.* introduced a wearable finger exoskeleton that consists of four links connected by revolute joints, one corresponding to each joint of the finger [87] [88]. For each joint of the exoskeleton, the flexion-extension direction of the finger was actuated. Remote Centers of Motion mechanisms are adopted for delocalizing the encumbrance of linkages of the structure away from the operator's fingers.

Among various transmission solutions, cable-driven transmission systems are most widely used in haptic gloves [19] [23] [27] [84]. Cable-driven solutions have the obvious advantages of small inertia, long distance transmission, and no backlash. The actuators such as motors can be mounted in a place distant to the fingertip, thus ensuring the small weight of the glove. The cable can be bent and twisted, permitting various passive finger motions, including adduction/abduction motion, and can transmit force even when the cable is bent around the joints. Therefore, the cables provide advantages of satisfying mobility requirements. However, it is difficult to design the mounting and control method, and thus to maintain the cable's tension [89] [90]. Specifically designed mechanical assembly and control algorithms are needed to ensure the performance of the cable driven systems.

4.5 Control

The function of the control system is to generate real-time force feedback command in response to the users' interaction with the virtual or remote environment.

One specific challenge of the control system is to accommodate the switch between two interaction states (free space and constrained space), as there are contradictory requirements from the two states. As we mentioned in Section 2.2, two control principles are used in designing haptic devices: impedance control and admittance control. Impedance controlled devices usually have low inertia and friction, and are highly back-drivable. They typically are able to render low-inertia, low-damping environments, but have difficulty emulating stiff constraints. In contrast, admittance controlled devices usually contain a transmission with a large reduction ratio, and thus are non-back-drivable due to high inertia and friction. They are capable of rendering high stiffness and large damping rather than low inertia. A force sensor is needed for admittance control. A systematic comparison between the two types of devices is available in [9].

The CyberGrasp uses impedance control to control the torque of the DC motor [23], which is transmitted by cable transmission to the fingertip cap. An encoder in each joint is used to measure the joint angle of each finger. The structure is fixed on the back of the hand to provide a sensation of external force on the fingertip.

Admittance control is seldom used in gloves, except for RML glove [41], as the haptic device based on it is usually non-backdrivable, and a high performance force sensor is needed to ensure a free space simulation sensation [9]. In RML glove, force sensitive resistor sensors were used to measure normal forces on the fingertip pad.

For existing impedance control gloves, an open-loop current control is normally used to control the torque of the motor. Only a few gloves used closed-loop force control, where a force sensor on the fingertip or on the actuator's axis was used to measure the actual force. For example, in [5], a force-sensing platform was constructed using four strain gauge sensors to measure the fingertip force. The measured force signals are fed back to adjust the actuated force, so that the desired force profile is perceived by the user [5]. It is a challenge to design small-sized force sensors while preserving the contact sensation of the fingertip.

An innovative glove design uses the "encounter-type" force feedback to meet contradictory requirements between free space and constraint space simulation [91] [92]. Using photodetectors, the glove is able to detect the free motion of the user's fingers. If the virtual hand is not in contact with a virtual object, the fingers of the glove are controlled to follow the user's fingers and to maintain no contact between the user's fingers and the glove. When the virtual hand contacts a virtual object, the glove fingers are controlled to make contact with the user's fingers and to apply forces. Recently, Song *et al.* proposed the concept of co-actuation to address the contradictory requirements between large stiffness and small inertia for designing haptic devices [93]. If a miniature design solution could be found, this concept might be applied to the design of a force feedback glove.

4.6 Structure design

An important problem in the structure design is how to mount the haptic glove on users' hands. The following issues need to be considered. First is the problem of skin deformation. When the hand moves for grasping a virtual object, the motion of the palm may cause a relative motion between the skin and the glove. This relative motion may introduce a clearance between the glove's mechanical structure and the hand. Therefore, when the virtual hand avatar contacts a virtual object (i.e. the avatar enters the constrained space, and a resistance force needs to be produced), the physical hand may not feel the force because of the clearance. The virtual hand may penetrate into the boundary of the virtual object until the clearance is fully compensated by further motion of the hand. This delayed sensation may greatly degrade the fidelity of the force feedback. To solve the above problem, the force transmission pathway should be analyzed to reduce the clearance caused by the mounting sub-system.

The next issue is the variation of hand sizes for different users. The adaptability of the system to different hand sizes needs to be studied for wearable haptic gloves.

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Reliable design solution is needed to ensure a reliable contact of the users' fingertip with the fingertip cap of the glove, and thus the feedback force can be exerted at the fingertip of the user. To make the glove adaptive for different hand sizes, some lessons can be learned from hand exoskeletons. Peculiar kinematic designs have been proposed to accomplish intrinsic adaptation of the hand exoskeleton prototypes to different hand sizes. Leonardis et al. proposed a 1-DoF mechanism that makes use of the user's own finger joints to close parallel kinematic chains [32] [88]. In the mechanism, three moving links are fixed on three phalanges, while the position of the axes of driving links can be adjusted to fit with different palm widths. Similar design concept combining the above parallel mechanism and other under actuation principles has been used in other hand exoskeletons [83] [44]. Fu et al. [94] developed a compact hand exoskeleton that utilizes an adaptive dorsal metacarpal base and five adaptive dorsal finger exoskeletons. In each finger module, a 2-DoF adaptation system is used to adapt different finger sizes. Brokaw et al. [95] presented a passive linkage-based device, in which the finger attachment points can be extended to adjust to different finger lengths, while the thumb attachment can be rotated to match the current user's thumb orientation. Lambercy et al. [96] developed a palm-grounded thumb exoskeleton able to provide forces at the fingertip. To adapt the exoskeleton to different hand sizes, the lateral position and orientation of the actuators can be adjusted to ensure proper alignment with the MCP joint. Moreover, the links can be adjusted to match the thumb length.

The third issue is the ergonomics of the glove, including rapid mount and dismount, light weight and comfortable sensation of the users, and aesthetics etc. Two types of mounting structures are widely adopted in force feedback gloves, i.e. Glove-type [23] [39] [42] or Velcro-type [5] [38] [40]. The glove-type system is simple to use; however, various sizes should be prepared for the users with different hand sizes. Velcro-type systems may be more flexible in terms of adapting to different hand sizes, but they require more time to put on than glove-type systems.

The last issue is the compact design of the sensing/actuation/transmission subsystems. In haptic gloves, all these subsystems including electronic circuits and control cards should be embedded in confined spaces, and ensure the profound dexterity of the hand without causing a burden for users.

5 Future Research Topics

In this section, future research topics and corresponding design challenges are elaborated.

5.1 Challenges of Fingertip Force Feedback Gloves

As shown in Fig. 5, there are two steps toward a high-fidelity force feedback glove for whole-hand kinesthetic feedback. As summarized in Table 1 of Section 3, most existing force feedback gloves mainly provide fingertip force feedback. As shown in Fig. 5, in this step, the goal is to provide accurate force feedback on the fingertip of five fingers. To meet the requirement of future mobile haptic interaction in the virtual reality era, it is necessary to explore innovative design solutions for improving the performance of current fingertip force feedback devices. The following four topics need to be addressed to fulfill this goal.

First, it is a challenge to meet the contradictive goals from both free-space and constraint space simulation, i.e. simulating the required impedance range while ensuring backdrivability for simulating free space sensation. As summarized in Section 3.2, very few force feedback gloves provide quantified performance data on the achievable impedance range and the backdrivability. As the impedance range may depend on several parameters from multiple sub-systems, including the resolution of position sensing, the control update rate, and the magnitude of actuators etc. Theoretical analysis is needed to model the effect of these parameters on the impedance range. Careful trade-off design of these sub-systems along with systematic optimization is needed to enlarge the impedance range while ensuring the backdrivability.

Considering the bulky actuation and transmission sub-systems of most existing gloves, the second challenge is to create portable devices that are small sized, light weighted, own wireless connections and a long battery life. A possible solution is to develop novel structures using smart materials that seamlessly integrate the functions of multiple components including sensing, controlling, actuation, communication and battery etc. [97].

Another challenge is to realize quick and personalized calibration for users with different finger length and hand sizes. As summarized in Section 4.6, existing design solutions normally require a time consuming procedure for securely mounting the mechanical structures on users' hand. Novel design solutions are needed to ensure quick calibration for force feedback gloves.

Finally, ensuring the low cost along with acceptable simulation fidelity will be a key factor that affects the large scale application of haptic gloves in diverse fields such as games, virtual reality and robotic manipulation. For example, head-mounted display has been developed over last three decades; however, the large scale application was only possible after the invention of the low cost Oculus Rift device. The cost of force feedback gloves may directly determine the accessibility of the haptic technology for virtual reality consumers.

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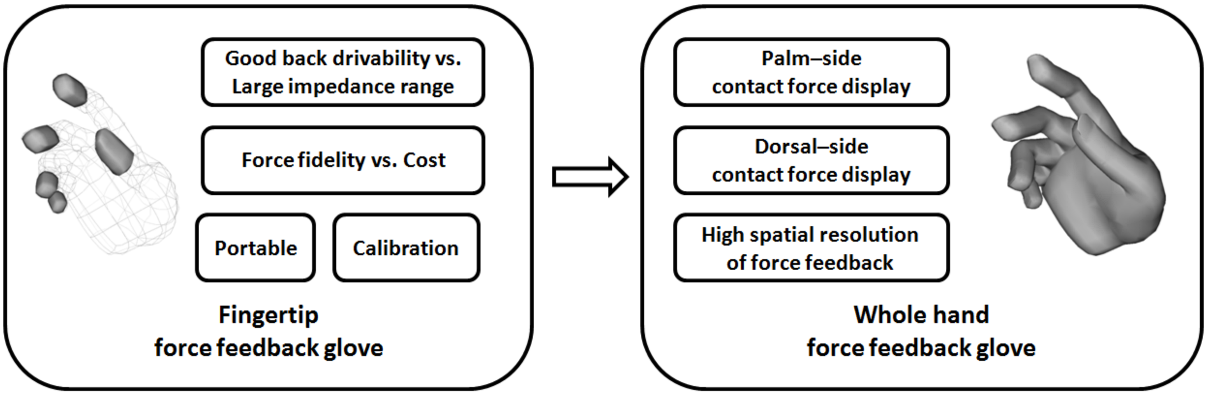


Fig. 5 Two steps toward whole-hand force feedback and research challenges (Pictures adapted from [10].)

5.2 Toward whole-hand force feedback

When we grasp an object, the contact points may not necessarily be on fingertips. Therefore, as shown in Fig. 5, in some applications, it may be beneficial to develop whole hand force feedback gloves which can not only provide fingertip force feedback, but also can provide distributed force feedback on the whole area of a palm.

An effective haptic glove should be able to simulate contact force from all possible contact points, and to support diverse grasping postures as elaborated by the taxonomy of grasping postures [98] [99]. As human skin is integrated with mechanoreceptors of variable density across its surface [100], novel actuation technologies that can produce high spatial resolution force stimuli on the skin need to be developed to fulfill the goal of distributed force feedback on multiple points of the palm's surface.

Furthermore, for the dexterous manipulation within a cluttered environment, the dorsal side of a hand may also contact the objects. In order to simulate this scenario, the contact force needs to be provided on the dorsal side of the fingers or the palm.

In addition to simulate distributed contacts between either palmar or dorsal surface of the hand and the virtual environment, another challenge is to produce force stimuli with sufficiently high spatial resolution that can match the spatial resolution of mechanoreceptors in the skin [3]. This requires a creative design using novel actuation technologies that can provide feedback forces covering the whole surface of the hand. Combining classic actuation technologies with emerging technologies from soft robotics [79] such as layer jamming [60] [110] may provide possible solutions to solve this challenging problem. New materials that couple sensing, actuation, computation, and communication should be explored [97]. Combined with microfabrication and assembly technology, smart structures integrating sensing/actuation capabilities may be one of the driving forces for developing novel and high-fidelity force feedback gloves.

5.3 Multi-modal haptic feedback gloves

In addition to force feedback, the next challenge is to provide tactile feedback, such as friction and textures on the glove. Nowadays, there are several solutions that can simulate tactile sensation to bare fingers, including the mechanical vibrotactile principle [101] [102] [103] [104] [105], squeeze film effect using piezo-electro vibration principle [106] [107], and electro-static effect [108] [109]. One remaining challenge is the miniaturization of these tactile devices, and thus integrating these devices into the fingertip locations of current force feedback gloves. A recent survey provided a systematic summary of wearable hand-based and fingertip-based devices providing cutaneous and kinesthetic stimuli to the whole hand [2].

The ultimate goal is to provide integrated haptic stimuli on the glove, i.e., not only force and tactile feedback, but also other subtle sensations such as thermal feedback, and skin stretch etc. For example, lateral skin stretch devices are able to apply a shear force to the skin. They exploit the high sensitivity of human skin to tangential stretch and can provide directional information [111] [112] [113]. Skin stretch and tangential motion stimuli may be combined to provide the illusion of slip for simulation of grasping a heavy object.

In order to develop a high-fidelity multi-modal glove, one technical challenge is the miniature design of different feedback modules, because it is difficult to embed several feedback modules in the compact space of a glove. These modules need to be integrated in a clever way that the spatial and temporal registration errors of different feedback cues can be controlled smaller than the sensory threshold of human users of perceiving multi-features.

A relevant fundamental research topic is the psychophysics study of multi-feature perception process. It is unclear whether the detection threshold on simultaneous perceiving multi-features might be different from perceiving a single feature. For example, thermal feedback on the hand may couple with the perception threshold on force magnitude [114] [115] [116]. In order to develop engineering plausible multi-modal haptic gloves, we need to study humans' perception characteristic on simultaneously perceiving different features.

5.4 Benchmark tasks for validating haptic gloves

The advancement of a novel technology relies on the driving force from *killer* applications; therefore, it is important to identify "suitable" tasks to manifest the necessary role of haptic gloves. To identify and develop *killer* application tasks, the following characteristics of human hand could be considered, including bimanual coordination, delicate and accurate finger movement/force control, and tasks requiring five fingers collaboration.

In order to enable cross-validation and evaluation of various haptic gloves, it would be interesting to learn from the DARPA challenges in robotics field to promote study of humanoid robot [117], or from the lessons from computer vision field, i.e. to organize competitions on algorithm comparison based on shared image database such as ImageNet [118][119]. Haptics community may consider the possibility of establishing a grand-challenge competition using some benchmark tasks, for example:

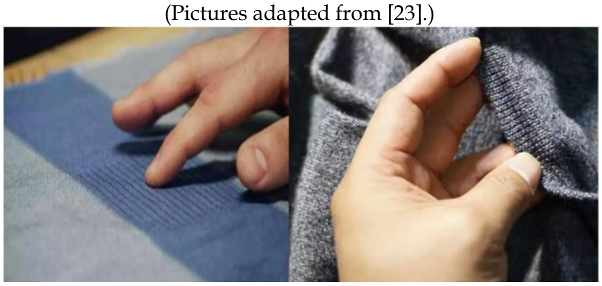
- Bi-manual nut-screw assembly: As shown in Fig. 6-a), twisting motion between the fingers and resistance torque control are necessary in this task. This will validate the workspace and fine force/torque feedback capability of the haptic glove.
- E-shopping of cloth/silk/feather: For e-commerce scenarios such as buying a garment or a sofa, users may like to touch and slide along the surface of the objects to obtain integrated sensation including softness, texture, and temperature. As shown in Fig. 6-b), two fingers are gently touching a sample of a garment using diverse gestures. This simulation task will validate the multi-feature feedback capability of the haptic glove. Furthermore, as users may use different gestures such as probing, stretching, rubbing etc., the glove should be able to support these gestures and ensure a natural interaction experience.
- Emotional communication in cyberspace: As shown in Fig. 6-c), the user might communicate with a virtual avatar through direct touch. One typical example is hand-shaking with a virtual shopping assistant or a virtual tour guide in virtual reality scenarios. These tasks require the glove to simulate whole hand force and tactile feedback with distributed contacts, along with thermal feedback for simulating emotional communication of the handshaking process.

6 Conclusion

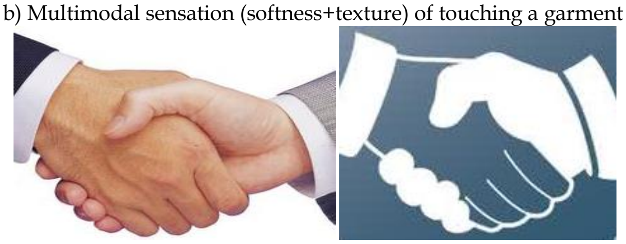
In this survey, towards a desired force feedback glove able to provide robust and realistic sensation of the interaction with virtual/real environments, we identified the gaps from the existing gloves, defined the challenges facing the design of the gloves at the levels of sensing, actuation, control, transmission and structure. Finally we pointed out the future research directions and topics.

Though force feedback gloves have been studied for over 20 years, it is still a great challenge today to simulate whole hand multi-feature haptic sensations including force, tactile, and thermal feedback etc. The challenges arise from the high density mechanoreceptors within the compact surface of human hand, along with the multi-DoF dexterous manipulation capability of the fingers. In the future virtual reality scenarios, realistic haptic sensation on users' hands will be a necessity to ensure immersion, interaction and imagination of virtual reality experiences. The solution for these challenges may rely on innovations in cross-disciplinary fields including material science, robotics, and deep understanding on biology and psychology of the human haptic channel.

a) Bi-manual sensation (force+torque) of assembling a screw-nut (Pictures adapted from [23].)



b) Multimodal sensation (softness+texture) of touching a garment



c) Multimodal sensation (force+tactile+thermal) during handshaking

Fig. 6 Illustration of some benchmark tasks for haptic gloves

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